

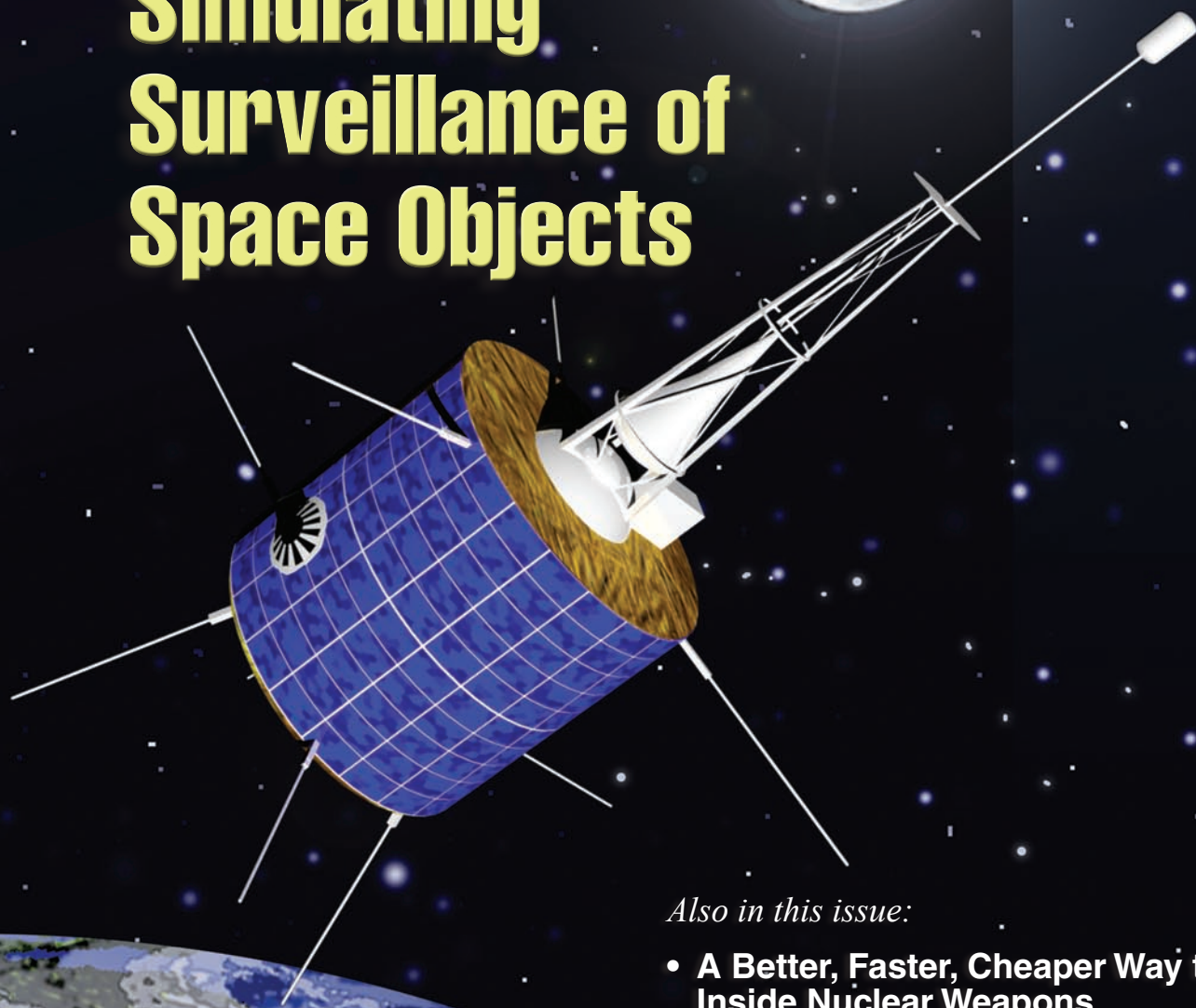
Science & Technology

REVIEW

July/August 2009

National Nuclear
Security Administration's
Lawrence Livermore
National Laboratory

Simulating Surveillance of Space Objects



Also in this issue:

- **A Better, Faster, Cheaper Way to See Inside Nuclear Weapons**
- **Laser-Target Interaction Generates Billions of Positrons**
- **Ultrawideband Technology Transfers to Medical Devices**

About the Cover

On February 10, 2009, a defunct Russian satellite (front cover) and a privately owned American communications satellite (back cover) collided in Earth's orbit—adding to the tens of thousands of pieces of debris already floating in space. As the article on p. 4 describes, a team of Livermore researchers, in collaboration with Los Alamos and Sandia national laboratories and the Air Force Research Laboratory, is working to improve the nation's capabilities for detecting and monitoring objects orbiting Earth to enable a more accurate assessment of whether or not orbiting objects pose a threat to any satellites. As part of this effort, experts at Livermore have been designing a comprehensive set of analysis, modeling, simulation, and visualization tools that together are called the Testbed Environment for Space Situational Awareness. (Artist rendering by Sabrina Fletcher.)



Cover design: Amy Henke. Cover rendering: Sabrina Fletcher.

About the Review

At Lawrence Livermore National Laboratory, we focus science and technology on ensuring our nation's security. We also apply that expertise to solve other important national problems in energy, bioscience, and the environment. *Science & Technology Review* is published eight times a year to communicate, to a broad audience, the Laboratory's scientific and technological accomplishments in fulfilling its primary missions. The publication's goal is to help readers understand these accomplishments and appreciate their value to the individual citizen, the nation, and the world.

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Please address any correspondence (including name and address changes) to *S&TR*, Mail Stop L-664, Lawrence Livermore National Laboratory, P.O. Box 808, Livermore, California 94551, or telephone (925) 423-3432. Our e-mail address is str-mail@llnl.gov. *S&TR* is available on the Web at str.llnl.gov.

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S&TR Staff

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WRITERS

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PRINT COORDINATOR

Charlie M. Arteago, Jr.

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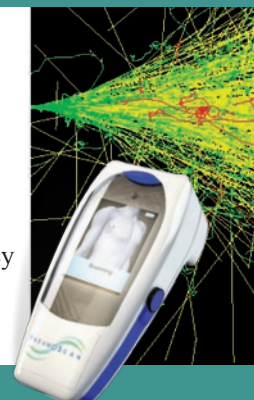
Portable medical diagnostic devices using ultrawideband technology help first responders evaluate injuries in emergency situations and could improve overall health care.

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NIF Dedication Marks Dawn of New Scientific Era

A dedication ceremony in honor of the National Ignition Facility (NIF) was held at the Laboratory on Friday, May 29, 2009. Among the more than 1,000 invited guests and 2,500 Laboratory employees that participated in the dedication were California Senator Dianne Feinstein and local Congressional Representatives Ellen Tauscher (Livermore), Jerry McNerney (Pleasanton), Zoe Lofgren (San Jose), and Governor Arnold Schwarzenegger. They were joined by the National Nuclear Security Administration's Administrator Tom D'Agostino, Department of Energy's Under Secretary for Science Steven Koonin, University of California's President Mark Yudof, and Lawrence Livermore National Security's Board of Governors Chairman Norman Pattiz.

The dedication marked the commissioning of NIF, the world's highest-energy laser system, which consists of 192 laser beams that will focus nearly 2 million joules of energy and create temperatures and pressures that exist in the cores of stars and giant planets. A new scientific era is about to begin. Researchers will be able to conduct a wide range of experiments never before possible on earth. "The laser fusion project will not only help ensure the safety and reliability of the nation's nuclear deterrent, but will also help lay the foundation for fusion energy and provide valuable insights into the very nature of the universe," said Tauscher.

Funded by the Department of Energy's National Nuclear Security Administration, construction of NIF began in 1997 with three scientific missions in mind. Its first mission is to serve as a key component of the National Nuclear Security Administration's Stockpile Stewardship Program to ensure the safety and reliability of the nation's nuclear deterrent without the need for nuclear testing. NIF also offers the possibility of groundbreaking scientific discoveries in planetary science and astrophysics; a large majority of these experiments will be unclassified and will provide a rich source of previously unobtainable data to research communities worldwide. NIF's third mission—energy independence—will entail focusing the lasers on a very tiny target filled with isotopes of hydrogen to produce a controlled fusion reaction similar to that found in the sun. "More energy will be produced by this 'ignition' process than the amount of laser energy required to start it," says Ed Moses, principal associate director of NIF and Photon Science. "This is the long-sought goal of 'energy gain' that has been the goal of fusion researchers for more than half a century."

Contact: Ed Moses (925) 423-9624 (moses1@llnl.gov).

Seed Persistence Is Well-Grounded

Scientists from Livermore and the University of Illinois at Urbana-Champaign (UIUC) have discovered that seeds of some tree species in the Panamanian tropical forest can survive for more

than 30 years before germinating—10 times longer than most field botanists had believed.

Using the Laboratory's Center for Accelerator Mass Spectrometry, the researchers measured the amount of carbon-14 in seeds of the trees *Croton billbergianus*, *Trema micrantha*, and *Zanthoxylum ekmanii* and found that seeds survived in the soil for 38, 31, and 18 years, respectively. Previous demographic studies of pioneer tree species had indicated that seed persistence (the ability to survive in soil, awaiting favorable conditions for germination) is short, lasting just a few years at most. However, in the tropical forests of Barro Colorado Island, Panama, they found the seeds of some pioneer trees remain viable for decades.

James Dalling of UIUC and Tom Brown of Livermore targeted sites in the forest occupied 20 years previously by species they suspected were capable of long-term persistence. After Dalling germinated seeds extracted from surface and soil layers at these sites, Brown carbon-dated samples taken from the seeds' coat. The results imply that buried seeds may be an important reservoir for genetic diversity in pioneer populations and may be as important as long-distance dispersal in maintaining populations in fragmented habitats. The team's research appeared in the April 2009 issue of *The American Naturalist*.

Contact: Tom Brown (925) 423-8507 (brown92@llnl.gov).

Maritime Exercise Shows off Radiation Detection

Several dozen military and law-enforcement officials tested their radiation detection equipment on the San Francisco Bay during a two-day exercise in April that was sponsored by Lawrence Livermore and the Monterey-based Naval Postgraduate School (NPS). The exercise focused on detecting nuclear materials and on screening small boats for similar materials.

Approximately 50 first responders from nine organizations searched for five radiation sources placed in three locations on the Maritime Administration's ship Keystone State, docked at the north end of Alameda Island. Their efforts included detecting radiation sources, training on the use of their equipment, and verifying whether radiation signatures showed characteristics of nuclear materials. On the second day, two Coast Guard boats were placed in position to form a portal. Seven other boats operated by the Coast Guard Auxiliary went through the portal, three with radioactive sources on board.

For NPS, the exercise offered a chance to study tools for rapidly deployable communications networks. For Livermore, the event permitted the study of radiation detection technologies in a maritime environment and further study of ultrawideband communications.

Contact: Bill Dunlop (925) 424-4462 (dunlop1@llnl.gov).



Game-Changing Science in the National Interest

LAURENCE Livermore has outstanding science, technology, and engineering (ST&E) capabilities that are brought to bear on important issues facing the U.S. and the world. We have an exciting mix of ongoing programs for sustaining our nation's nuclear weapons stockpile, reducing the danger of global security threats such as proliferation of weapons of mass destruction, and meeting the worldwide need for abundant energy with a greatly reduced environmental impact. Progress in each of these mission areas depends on breakthroughs made possible through the multidisciplinary application of leading-edge science and technology.

To remain at the forefront of ST&E research and meet existing and newly arising national security needs, the Laboratory must constantly think ahead: What are the biggest challenges of the 21st century? What science and technology breakthroughs are needed to provide “game-changing” solutions in response to these challenges? Where can Livermore most effectively make a difference in applying and advancing its unique research capabilities?

Earlier this year, we addressed questions such as these as part of a 100-day study that defined a future course for the Laboratory in its role of providing ST&E research in the national interest. We identified six mission-specific thrust areas. Teams were formed to outline big, audacious goals in those areas and elucidate the necessary ST&E breakthrough advances for achieving them. The result of the study is a five-year road map, which we will continually update, that specifies the internal investments and program-building efforts we foresee will be needed to meet critical national needs. Our planning efforts identified a number of exciting opportunities to serve the nation.

“Intelligence, space, and cyber security” is one of the mission areas where we identified specific needs. In a rapidly changing world dense with information, it is critical that we make the best use of available data to understand foreign threats to national security and to protect assets the U.S. relies on to stay informed. With its expertise in high-performance computing and data management, the Laboratory is examining advanced methods for extracting information from data to improve intelligence analyses. We also are developing new simulation tools for improving situational awareness for both cyber security and the protection of space assets.

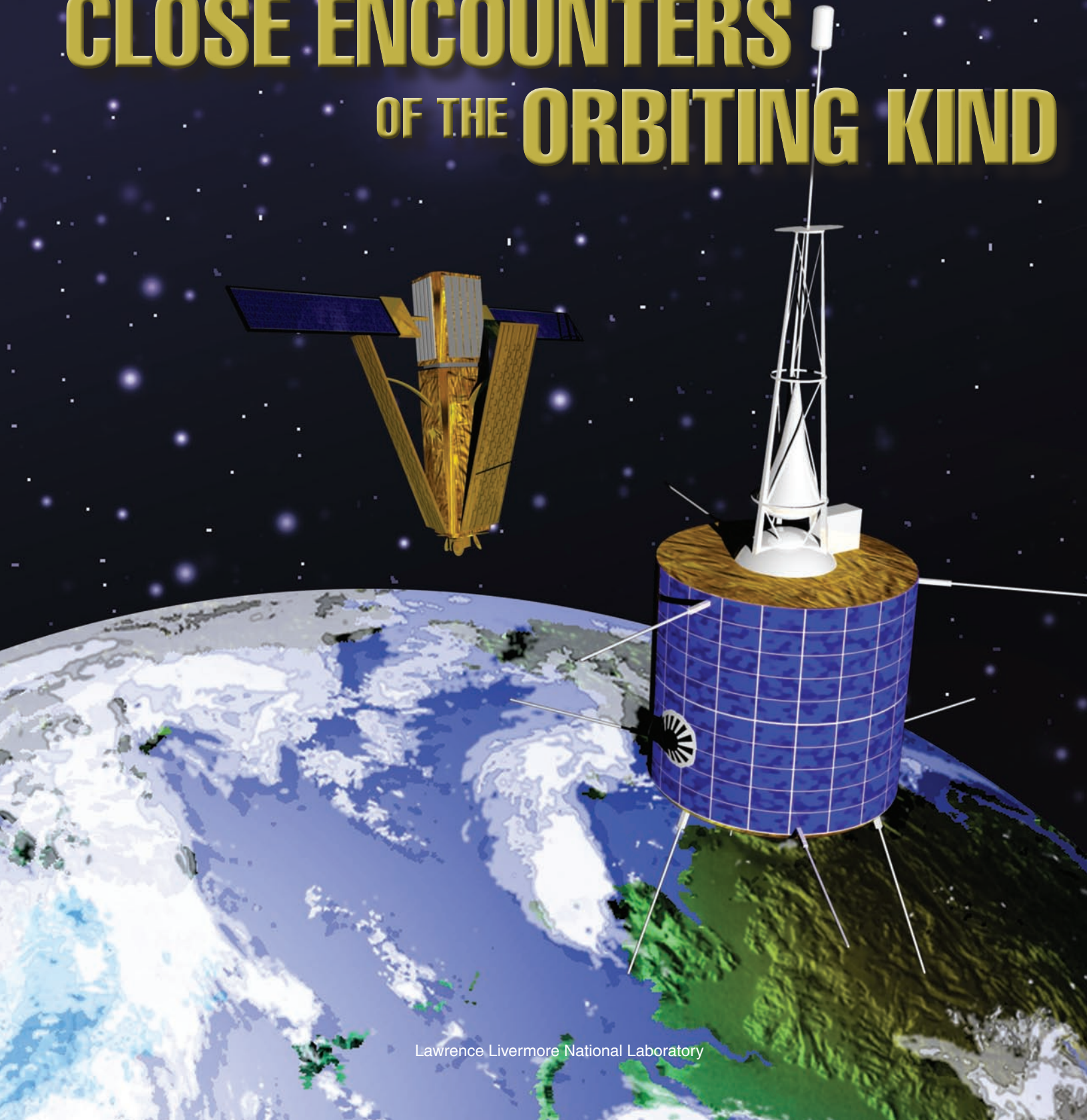
The article beginning on p. 4 describes Livermore's groundbreaking work to improve situational awareness in space. The development of the Testbed Environment for Space Situational Awareness (TESSA) began about a year before the world was surprised with headline news of a collision between a defunct Russian satellite and an American communications satellite on February 20, 2009. The event resulted in the spread of even more debris in orbit around Earth, increasing the risk of damage to satellites vital for U.S. security and humankind's day-to-day activities.

TESSA simulates the positions of satellites and space junk orbiting Earth and the detection and tracking of them by telescope and radar systems. A goal of the project is to provide a high-fidelity simulation model of the Air Force's Space Surveillance Network, which has the task of knowing the location of many thousands of objects in orbit and assessing whether or not any of these objects pose a threat to any active satellites. The project aims to demonstrate methods for combining improved orbital prediction capabilities with observational data to better determine the likelihood of space collisions. The work is part of a broad collaborative effort involving Livermore, Los Alamos, and Sandia national laboratories and the Air Force Research Laboratory to improve space situational awareness.

Internal resources such as funding from the Laboratory Directed Research and Development Program have supported our early work on TESSA. The project is an example of how forward-thinking efforts to further enhance and focus the Laboratory's exceptional ST&E capabilities can serve the nation and help to tackle its most important challenges.

■ Tomás Díaz de la Rubia is acting principal associate director for Science and Technology.

PREVENTING CLOSE ENCOUNTERS OF THE ORBITING KIND



*Livermore researchers are
designing simulations and other
tools to help prevent collisions
in space.*

HUNDREDS of active satellites as well as tens of thousands of pieces of space junk—defunct satellites, bits of booster rockets, and lost astronaut tools—orbit Earth. Space junk was suddenly front-page news on February 10, 2009, when a defunct Russian satellite and a privately owned American communications satellite collided near the North Pole. The incident produced clouds of debris that quickly joined the orbital parade, increasing the possibility of future accidents.

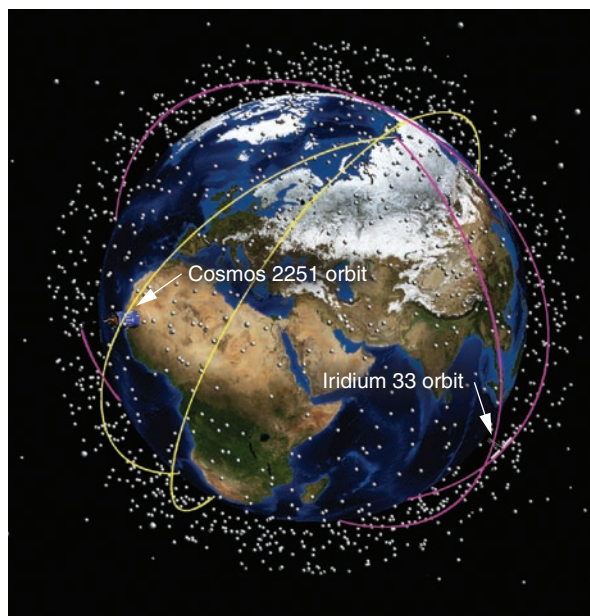
Space scientists were aware of the potential for a close encounter between the Russian and U.S. satellites before they crashed, but the difficulty of precisely predicting orbital paths made a definitive prediction of the collision impossible. More than 80 countries have joined the space community, making Earth orbit an increasingly congested—and contested—piece of aerial real estate. Just last March, astronauts aboard the International Space Station had to briefly seek refuge in their Soyuz escape capsule because of concern about a piece of space junk that might hit the station. The debris missed.

Lawrence Livermore, in collaboration with Los Alamos and Sandia national laboratories and the Air Force Research

Laboratory, is working to improve the nation's capabilities for detecting and monitoring threats to U.S. space operations. Since early 2008, a team of computational physics and engineering experts at Livermore has been designing a comprehensive set of analysis, modeling, simulation, and visualization tools that together are called the Testbed

Environment for Space Situational Awareness (TESSA).

TESSA simulates the positions of objects in orbit and the detection of them by telescope and radar systems. Initial goals of the collaborative project are to provide a high-fidelity model of the Air Force's Space Surveillance Network (SSN), which is tasked with knowing the



(Opposite page) On February 10, 2009, the defunct Russian Cosmos 2251 satellite (foreground) and the privately owned American Iridium 33 satellite (background) collided in Earth's orbit. (Rendering by Sabrina Fletcher.) (Left) A Livermore visualization shows the orbits of the two satellites prior to the collision among the hundreds of other orbiting satellites. The collision occurred where the two orbital paths cross—over Siberia near the North Pole.

location of objects orbiting Earth, and to enable a more accurate assessment of whether or not any orbiting objects pose a threat to any active satellites. In addition to enhanced space situational awareness, such a simulation system could in the future be used to help plan sensor operations and assess the benefits of specific sensor systems, technologies, and data analysis techniques.

An impetus for improved space situational awareness was a 2007 event in which China shot one of its own defunct satellites. “The incident not only reinforced the vulnerability of satellites in space but also revealed the need for a better understanding of debris dispersion following a high-velocity collision,” says

Livermore physicist Scot Olivier, who leads the TESSA effort.

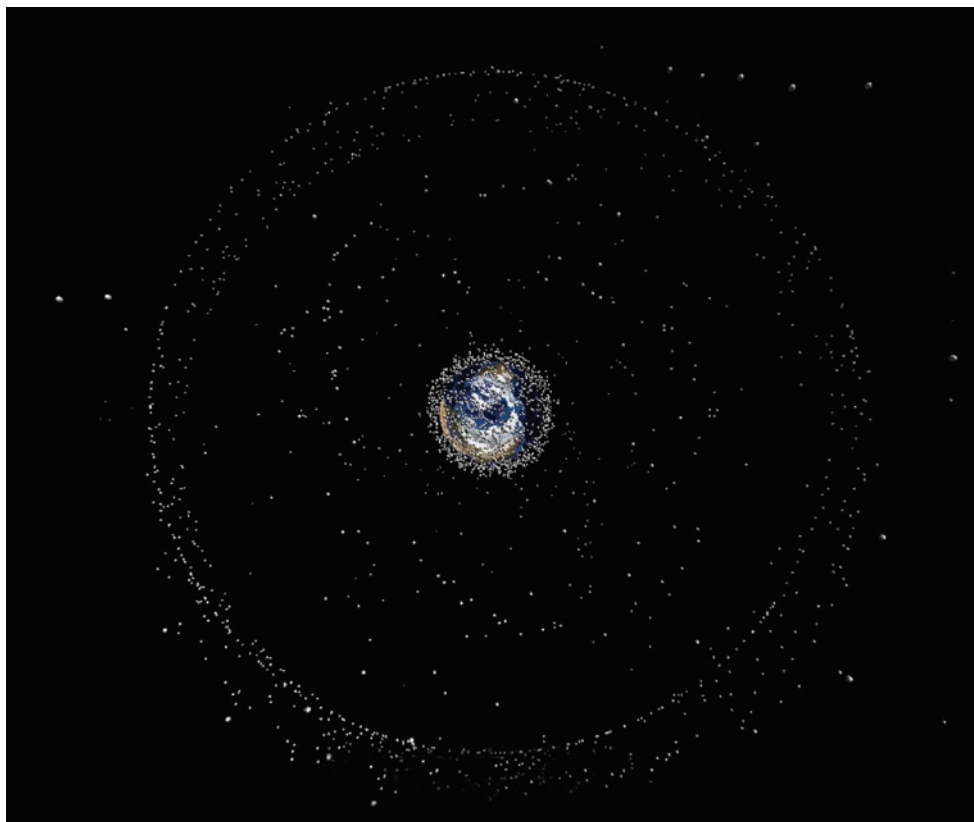
An object the size of one’s thumb could inflict massive damage on impact when moving at hypervelocity—several kilometers per second or more. Damage to an active satellite could have far-reaching repercussions. Orbiting satellites are vital links in worldwide data, voice, and video communication systems. Some satellites help to connect people in remote regions and others help to navigate ships, aircraft, and land vehicles. Satellites also help to advance scientific studies by providing data critical for Earth, marine, and atmospheric science research. The primary function of about one-quarter of all satellites is to support defense systems for countries around the globe.

SSN maintains telescope and radar systems to track and catalog objects detected in Earth’s orbit. Radar systems track most objects in low Earth orbit, from 200 to 1,000 kilometers above Earth, while ground-based telescopes primarily monitor satellites in geosynchronous Earth orbit, nearly 36,000 kilometers above Earth. SSN can track objects about the size of a softball, or 10 centimeters in diameter, in low Earth orbit and objects about the size of a basketball in the higher geosynchronous orbit. A U.S. surveillance network has been in place since the former Soviet Union launched Sputnik, the world’s first satellite, into space in 1957.

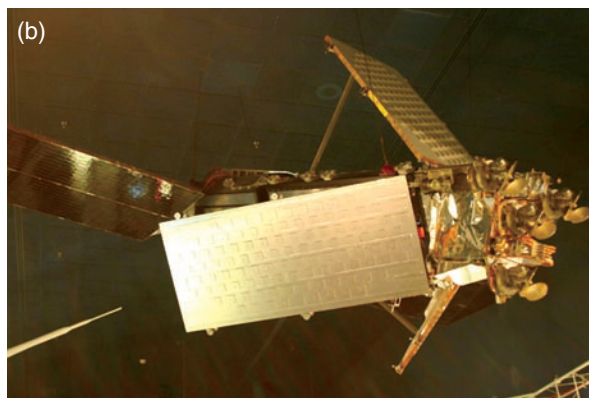
With TESSA, the Laboratory is improving the capability to analyze the performance of SSN’s imaging and detection systems and assess the relative efficacy of new configurations and methods. Livermore has committed Laboratory Directed Research and Development funding as well as other sources of internal funding to implement TESSA, which exploits the Laboratory’s expertise in high-performance computing; optical and radio-frequency phenomenology and instrumentation; and the physics of hypervelocity impacts. More recently, the TESSA project has attracted funding from external sponsors, through the efforts of Olivier and Global Security Directorate deputy program director Dave Dye, who is responsible for program development initiatives. Physicist Alex Pertica is project manager and chiefly responsible for project execution.

The Real Deal

The February 10 collision jolted not only two satellites but also the urgency of the TESSA team’s work. “It provided the first opportunity for Livermore to use its modeling tools in a live situation,” says Pertica. The collision involved Cosmos 2251, a defunct Russian satellite, and Iridium 33, one of 90 satellites flown by Iridium



The tight collection of tiny dots close to Earth are satellites and space junk in low Earth orbit, between 200 and 1,000 kilometers above the surface. Other objects revolve in the much higher geosynchronous Earth orbit, nearly 36,000 kilometers above the surface. In between are a few objects that circle the planet in highly elliptical orbits.



The February 10 collision involved (a) Cosmos, a 3- by 2-meter cylindrical Russian satellite, and (b) Iridium 33, a 2-meter-long, antenna-laden American satellite.

Building TESSA

Some simulations using the Testbed Environment for Space Situational Awareness (TESSA) are based on techniques widely used at the Laboratory. For example, hydrodynamic simulations of the February 10, 2009, collision near the North Pole between a defunct Russian satellite and a privately owned American communications satellite show processes that occur continuously over time. The simulations mathematically break the collision, or intercept, into a grid and calculate all of the interactions that occur over the 100-millisecond time span of the collision and breakup.

Other aspects of TESSA simulations are more unique. Modeling the activity of radar systems and telescopes that track objects orbiting Earth requires a completely different simulation methodology. A telescope may pan the sky keeping stars in a fixed position. Satellites and other orbiting objects move in and out of the field of view, creating streaks across the sky. Radar is often programmed to jump around the sky, collecting information from various areas in quick succession. “To simulate the tracking of orbiting objects, we are examining discrete changes in state, not a continuous process,” says Livermore’s David Jefferson, who designed the TESSA framework. “Discrete event simulation is primarily concerned with discontinuities in a system’s behavior rather than the continuous parts.” Examples of other situations that require discrete event simulation are missile defense, national infrastructure, computer networks, particle systems, and air traffic control.

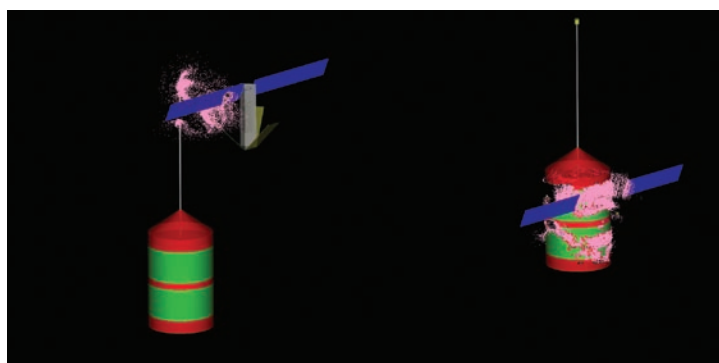
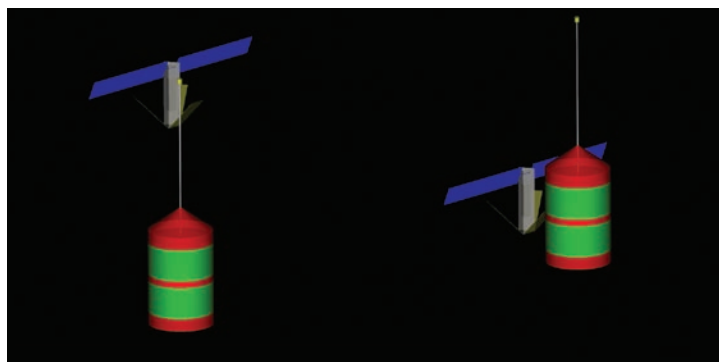
In the 1980s and 1990s, long before he arrived at the Laboratory, Jefferson worked with other experts around the country to develop methods for parallel discrete event simulation (PDES). The TESSA PDES architecture is based on two Livermore programs, Babel and Co-op. Babel earned a 2006 R&D 100 Award for its flexibility in communicating among programs written in different programming languages. (See *S&TR*, October 2006, pp. 8–9.) High-performance applications in different languages can interoperate, allowing them to pass scientific data seamlessly and efficiently from one another. Co-op was built upon Babel and is a tool that allows parallel components to

run different codes at the same time. The Co-op style of parallelism is described as “multiple programs, multiple data,” in contrast to “single program, multiple data,” the usual style of parallelism for scientific computations and simulations. A single processor may be able to simulate all of the data from a radar device, but multiple processors are needed to simulate what a telescope sees, and TESSA accommodates that difference.

In a continuum simulation, all parallel processes need to be synchronized in time. In PDES, however, the processors are not all handling data from the same moment in simulation time. “The big challenge with PDES is maintaining enough synchronization that all processors are used efficiently,” says Jefferson. “The processors handling data farther ahead in time cannot interact with those that are behind. We have to maintain causal relationships, which are always directed forward in time. Livermore is good at big simulations on big computers. TESSA is a striking new example.”



Hydrodynamics simulations using the ParaDyn code show (from top to bottom) two possible geometries for the Cosmos (red and green) and Iridium (gray and blue) satellite collision. On the left, the satellites barely clip one another, and on the right, the satellites meet head-on. The simulations begin at initial impact and continue for just less than 100 milliseconds.



Corporation in low Earth orbit. An analysis of archive data showed that during the previous two years, nearly 200 close encounters, or conjunctions, occurred when the paths of Cosmos 2251 and Iridium 33 came within 100 kilometers of each other.

Livermore's initial analysis of the event, based on publicly available data, established a closing speed and strike angle for the collision, or intercept. The closing velocity proved to be almost 12 kilometers per second, or more than 30 times faster than a speeding bullet.

At the time of the collision, much information was still lacking. Says Keo Springer, an expert in hypervelocity impact modeling, "It was unclear whether the satellites collided head-on or clipped each other. The degree of overlap of the colliding satellites, as well as the closing speed, strike angle, and material composition, can influence debris size and velocity distributions."

Springer used Livermore's explicit hydrodynamics code ParaDyn (parallel DYNA3D) to simulate several possible geometries for the impact and resulting debris. The simulations cover about 100 milliseconds, from the initial impact through breakup and fragmentation of all or parts of the satellites. The collision is now estimated to have generated upward of 1,000 pieces of debris large enough to be tracked by SSN.

As part of an earlier project, Springer and his team had upgraded ParaDyn to include smooth particle hydrodynamics. This enhancement improved ParaDyn's hypervelocity impact modeling capability by more accurately capturing the pressure-volume response of highly deformed material. A member of that team, computer scientist JoAnne Levatin, also developed DFRAG, a code that characterizes each piece of debris from a hypervelocity collision, including its mass, velocity, and material type. Levatin has since refined DFRAG for TESSA.

Don Phillion, an expert in orbital mechanics, used an orbital propagation code to “launch” all of the debris into orbit. In the past, he performed simulations such as these with SGP4, a standard orbital propagator. Recently, Phillion began using a much more accurate force model that captures all of the physics, including the forces represented by the Sun and Moon, solar radiation pressure, and atmospheric drag. The gravitational perturbations caused by our Sun and Moon cause the ocean tides and are powerful enough to deform our solid Earth 10 to 20 centimeters with every change of the tides.

The data on orbiting satellites and debris were passed to Ming Jiang, a computer scientist who specializes in managing and processing large-scale geospatial information. Using the ViSUS software developed during an earlier Laboratory Directed Research and Development project, Jiang produced a full-scale, physics-based visualization of the collision and its aftermath. “The ViSUS software can handle both the imagery and geometry from extremely large data sets,” says Jiang. The images show a high-resolution “blue marble” image of Earth along with satellite positions and debris geometry in fine detail. Phillion’s code calculated the position and velocity of objects and debris every 10 seconds.

Jiang’s visualizations of the debris, which cover the first 24 hours after impact, unexpectedly revealed that the debris did not orbit in a smooth ring but instead became a tight spiral around Earth. Says Jiang, “The spiral was caused by debris pieces moving at varying speeds combined with the orbital dynamics that govern the motion of debris.” Olivier notes, “This unexpected finding highlights the importance of visualizations. Physical properties were uncovered that would otherwise be difficult to predict.”

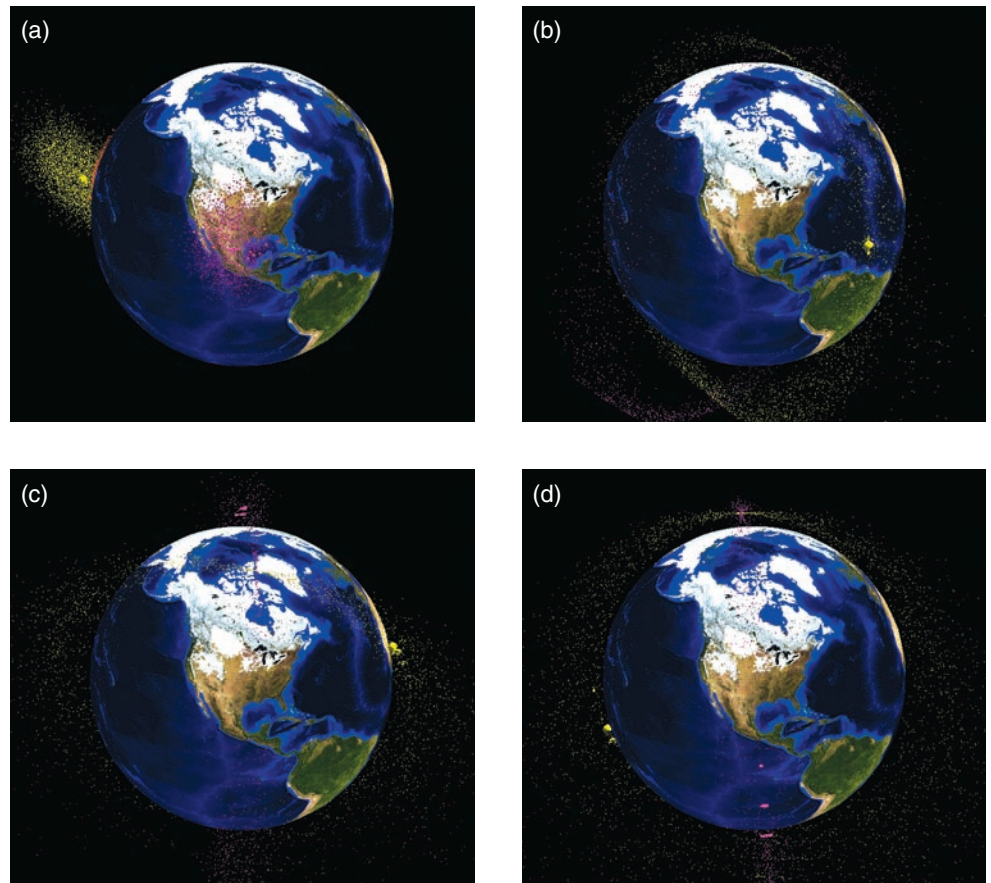
The \$64,000 question asked after the February 10 collision was “Would any of

the debris threaten anything else in orbit?” Since the collision, some of the debris has fallen out of orbit and re-entered Earth’s atmosphere. Other pieces have fallen into lower orbits where the International Space Station and the Hubble Space Telescope revolve. So far, all is well.

“Close calls happen all the time,” notes physicist Willem DeVries, who is improving codes that predict conjunctions between orbiting objects. “The U.S. needs the capability to predict close calls and potential collisions. However, conjunction analysis being performed by the Air Force today is

not sufficiently accurate, resulting in too many false alarms to be useful for satellite owners.” The codes can accurately identify situations involving the risk of a satellite collision or increased threat levels from the generation of new debris. However, they cannot predict specific collisions because intrinsic positional uncertainties are on the order of 1 kilometer.

The Air Force’s Joint Space Operations Center, headquartered at Vandenberg Air Force Base, California, has been tracking Iridium–Cosmos debris since the collision. DeVries performs simulations in an effort



Visualizations show (a) the debris from Cosmos (yellow) and Iridium (magenta) is initially in two clouds just after the satellites collide. (b, c, d) In the hours following the collision, the debris spreads out in the same orbits as the two satellites. The satellites’ orbits were essentially perpendicular to one another, crossing near the North Pole. The collision left some particularly large chunks of debris. (The debris is magnified 20,000 times for better viewing.)

to match conjunction rates of the TESSA model debris to observed debris. However, matching the Air Force’s data with Livermore’s modeled debris has not been without problems.

“The debris is dispersing more slowly than our code predicts,” says DeVries, “so scientists are speculating how the collision actually occurred. A full body-on-body collision would have produced far more fast-moving debris. It’s possible a smaller overlap collision occurred in which the satellites broke up gradually.”

Inside TESSA

On a typical work day, one without a satellite collision, TESSA team members simulate telescope and radar views of the sky and comb the data to find indications of satellites and other orbiting objects. They use these simulations to test if actual collected data combined with more sophisticated orbital mechanics models

can be used to refine the orbit of a known object or identify a new object.

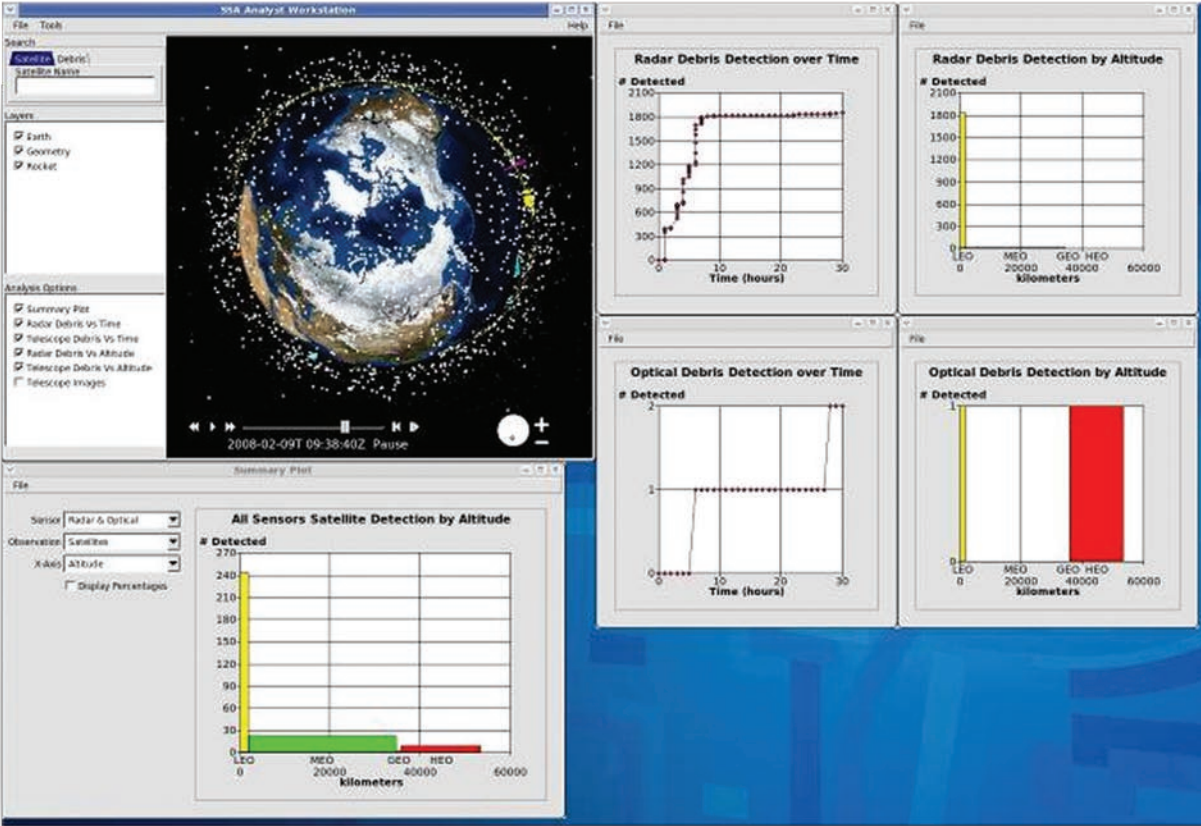
TESSA consists of an easy-to-use setup program at the front end and Jiang’s interactive visualization program at the back end, both of which can be accessed from a team member’s desktop. In between is the TESSA parallel discrete event simulation (PDES) system. (See the box on p. 7.) TESSA includes a cycling process that moves data from one module to the next, and more than one code can be running at a time. Simulation results feed a growing database of orbiting objects, and this information cycles back to the front end of future simulations for ever-greater accuracy. TESSA’s PDES system runs on Livermore’s HERA, a high-performing computing cluster, and typically uses hundreds of central processing units for a single run.

Most TESSA simulations of objects orbiting Earth include possible debris

from the February 10 intercept, the 2007 Chinese satellite intercept, or hypothetical intercepts. Detailed intercept simulations based on an actual scenario can also be computed and the data stored for future use. Results of a potential intercept with close to the same parameters can then be interpolated from this precomputed data when the effects from changes in the intercept parameters (for example, relative velocity and angle of impact) are modeled.

Physicist Sergei Nikolaev simulates telescope images, which typically are of objects in geosynchronous Earth orbit. “Initially, we used open-source, commercial software to model telescope response because we needed to start up quickly last year,” says Nikolaev. A standard astronomical image simulation code, SkyMaker, was combined with a U.S. Naval Observatory star catalogue, debris data, scattered sunlight, moonlight, sky background, and the Air Force’s

The TESSA User-Defined Operational Picture is a customizable environment for visualizing orbiting objects and the results of simulations. This graphical user interface is available on the desktop of all TESSA users.



satellite catalogue, which is updated several times per day.

Another part of this “optical detection pipeline” was a software program to measure the position of stars and satellites in the resulting images. Nikolaev has since developed a more flexible and feature-rich software program for processing simulated images.

Telescopes are typically operated in sidereal tracking mode, which keeps the stars as fixed points in a telescope’s field of view. Simulated telescopic images show a satellite motion as a streak against a background of stars. A series of simulated images over time will show a series of streaks. Levatin wrote Livermore’s Aggregator software, which is at the end of the optical detection pipeline. Aggregator contains algorithms that examine position data for consecutive streaks to determine if they are in fact from a single orbiting object. Three or four streaks may thus be pieced together and identified as the track of a single satellite.

Simulating a radar system’s view of the sky is quite different. Radar does not “see” stars. Rather, it detects stars in patches of sky in quick succession, or in the case of multiple radars, detects a single part of the sky from many angles. Ben Fasenfest, an electromagnetic code specialist, uses the EIGER code to simulate about a dozen radar systems belonging to various U.S. agencies for monitoring satellites in low Earth orbit.

The EIGER radar simulations are combined with debris simulations from ParaDyn and DFRAG as well as from models for existing satellites and space junk. “The models look at the sky and check for objects in their field of view,” says Fasenfest. “EIGER measures the radar cross section—the power coming back to the radar—of each object it sees and categorizes the objects by these cross sections.” Distant objects are typically harder to measure.

Simulated telescope and radar data flow into Phillion’s orbital mechanics codes, which determine and propagate an orbit

for every observed object. Orbital data is matched to known satellite and debris orbits. TESSA data tests how effectively actual data can be used to improve on known parameters for orbiting objects. The data may also reveal a new object or piece of debris. This information is added to the TESSA database and helps to make future simulations even more accurate.

Improving TESSA

Phillion notes that TESSA’s simulations at this time do not incorporate a feedback feature. The schedules for telescope and radar observations are fixed in advance. “Use of the preplanned observational model is giving us better orbital data,” says Phillion. “However, if a simulation reveals an unknown object or a potential conjunction, we currently don’t have a way to quickly take another look.”

Livermore brings to the TESSA project extensive experience in “data mining,” a statistical process that quickly sifts through mountains of information to locate the important nuggets. This capability is key for developing new tools that analyze sensor data and provide rapid feedback to the sensors to shift their attention toward the site of a possible collision. This feedback loop, which is still in the planning stages, would vastly improve the capability to protect U.S. space assets.

In July 2009, a new high-performance computing cluster is scheduled for delivery to the Laboratory’s International Security Research Facility. It will be used extensively for TESSA and will allow the team to perform simulations that contain sensitive data.

In addition, the TESSA team has been working with a relatively new form of high-performance computing called general-purpose computation on graphics processing units, which use high-density processors originally developed for fast-graphics processing and computer gaming to speed up parallel calculations. TESSA’s Linux workstation-based system contains

960 graphics processing units in a chassis the size of a pizza box. This new system is expected to speed up DeVries’s conjunction analysis a hundred times more than a single central processing unit. It will also allow for higher-resolution calculations involving smaller pieces of space junk. SSN currently monitors about 13,000 objects because of limits to what its sensors can routinely follow. Experts believe that more than 100,000 potentially lethal objects may be orbiting Earth.

Because of the 2007 Chinese satellite intercept, TESSA initially focused its efforts on debris simulations. “Now, the scope is much broader,” says Olivier. “We are modeling space operations in a unified framework and moving from surveillance to a broader awareness of what is occurring in space. We need the capability to quickly and accurately predict an event, such as a collision, before it occurs.”

The U.S. Air Force Space Command and the National Reconnaissance Office have joined to create a new national program to coordinate space-protection activities across the military and intelligence communities. TESSA is now being used to support these activities and could eventually be fully integrated into the Joint Space Operations Center.

—Katie Walter

Key Words: high-performance computing, Joint Space Operations Center, ParaDyn (parallel DYNA3D), parallel discrete event simulation (PDES), space situational awareness, Space Surveillance Network (SSN), Testbed Environment for Space Situational Awareness (TESSA), ViSUS.

For further information contact Scot Olivier (925) 423-6483 (olivier1@llnl.gov) or Alex Pertica (925) 423-3354 (pertica1@llnl.gov).

A CAT SCANNER FOR NUCLEAR WEAPON

*A new x-ray
inspection
system gives
scientists a three-
dimensional
view inside
nuclear weapon
components.*

THE Department of Energy's National Nuclear Security Administration (NNSA) is looking to accomplish even more within its budget constraints, as it pursues a smaller, safer, more secure, and less expensive nuclear weapons complex. Meeting that goal means relying on advanced scientific tools and procedures to assure a high level of confidence in the performance of aging weapons in the stockpile. The longer confidence in the performance of an aging weapon system can be assured, the longer the nation can keep the system as part of a credible nuclear deterrent without having to refurbish the weapons or produce replacements.

In response to NNSA's needs, Livermore physicists, engineers, and computer scientists have developed a new computed tomography (CT, also known as computerized axial tomography or CAT) x-ray system to image nuclear weapon components removed temporarily

COMPONENTS

from the stockpile for inspection. The Confined Large Optical Scintillator Screen and Imaging System (CoLOSSIS) consists of a scintillator (a material that emits light when struck by ionizing radiation); a pyramid-shaped central mirror; four turning mirrors; and four high-resolution, low-intensity visible-light charge-coupled-device (CCD) cameras. The system's software assembles the collected digital radiographs into a large three-dimensional (3D) image that scientists can "walk through" to discover any problems or anomalies.

CoLOSSIS was recently installed at NNSA's Pantex Plant near Amarillo, Texas. The overall CT system includes a 9-megaelectronvolt (MeV) linear accelerator and a tungsten target (built by Varian, Inc.) that produce the x-ray beam, three tungsten collimators that shape the x-ray beam and prevent unwanted scatter, and a positioning table that securely holds the test object and

rotates it in precise increments for the CoLOSSIS detector.

A typical CoLOSSIS inspection comprises about 1,500 separate radiographic images taken of an object from all sides. The radiographs are then assembled, using Livermore-developed tomographic image algorithms, to provide a 3D reconstructed image with greater resolution than previously achieved using a 9-MeV x-ray system. Nearly all elements of the inspection system—x-ray source, collimators, positioning table, detector, and tomographic algorithms—contribute to its high-resolution capability.

Pantex is the nation's only nuclear weapons assembly and disassembly facility. To maintain the reliability of the nation's nuclear weapons stockpile, weapons are randomly selected and transported to Pantex for testing and evaluation. X-ray radiography is used to probe inside the nuclear pit of a weapon in a nondestructive manner;

that is, the weapon does not have to be dismantled. Plutonium pits are one of the most important components routinely inspected. Tests on these pits can reveal structural variations arising from so-called birth defects (manufacturing flaws) or from aging. Potential variations include cracks, voids, gaps, and density variations.

Livermore chemist Pat Allen, deputy program manager of the Laboratory's enhanced surveillance effort, says, "Without x-ray diagnostic tests at Pantex, we would have to resort to destructive evaluation of these very expensive weapon components. With the right diagnostic tools, we can conserve valuable resources by eliminating some destructive procedures and disassembly operations."

"Livermore's role in helping to develop CoLOSSIS reflects the strong nondestructive evaluation capability at the Laboratory," says Allen. A core competency at Livermore, nondestructive evaluation



X rays from a 9-megaelectronvolt (MeV) linear accelerator (far right) travel through three tungsten collimators to the heavily shielded Confined Large Optical Scintillator Screen and Imaging System (CoLOSSIS).

is a means of examining and identifying flaws and defects in materials without damaging them. Laboratory engineers routinely use x-ray, ultrasonic, acoustic, infrared, microwave, visible-imaging, and other noninvasive techniques to examine defects, measure properties, and accurately determine part thicknesses of materials for a variety of research programs.

CoLOSSIS is currently undergoing final qualification at Pantex. Future inspections at Pantex will generate important data for scientists and engineers at Lawrence Livermore and Los Alamos national laboratories, the two centers of nuclear weapon design and engineering.

Quest for Higher Resolution

Allen notes that although current x-ray inspection procedures at Pantex are working well, scientists would like to achieve even better contrast and resolution. “We want to see finer detail and be able to differentiate one material or feature more easily from another,” he says.

Livermore physicist Jim Trebes says that traditional black-and-white film can exceed the resolution of digital radiography in a single image. However, film has certain drawbacks. For example, many people with film expertise have retired, the film industry is in deep decline, and environmental controls on film-processing chemicals are increasing. The

biggest drawback to film, though, is that it does not lend itself easily to processing 3D views. Trebes says, “If we know a feature exists in a certain location, we can easily record it with film. However, if we are performing a survey to look for problems, 2D film radiography is not sufficient because a subtle region can be obscured by another material or component.”

Recognizing film’s limitations, NNSA managers urged the development of a CT system to be installed in an existing x-ray inspection bay at Pantex with a goal of obtaining greater resolution and contrast to detect even the slightest manufacturing flaws and changes in materials from aging. With 3D imaging, scientists could examine any discrepancies from many different angles. “We want to see features as small as 2 or 3 mils (thousandths of an inch), equivalent to 50 to 75 micrometers, in very-high-density components,” says Allen. “The best resolution for 9-megaelectronvolt x-ray CT has until recently been 6 to 8 mils, or 150 to 200 micrometers.”

CT scanners are commonly used in the medical field to take multiple radiographic views of a patient and then compute them into 3D images. More than 30,000 CT scanners worldwide are in use, mostly in hospitals. A medical CT scan is performed by rotating the x-ray source and detector around the patient. In contrast, CoLOSSIS

does just the reverse: The x-ray beam and detector remain stationary, while the object is rotated 0.25 degrees for each succeeding picture.

Trebes notes that Livermore researchers regularly perform CT x-ray scans to examine tiny fusion targets for the National Ignition Facility, the world’s most energetic laser. They also certify critical components for the National Aeronautic and Space Administration and for U.S. manufacturing companies.

Applying digital CT to weapons inspection poses a particular set of challenges. The procedure requires a source of x rays (typically an electron accelerator), a stage to position and move the object, a detector (scintillator), cameras to capture the image, and software to process the images. The source-object-detector configuration must be both thermally and vibrationally stable to avoid blurring the image. The room must be shielded to reduce backscatter into the detector and to protect the electronics and any personnel located in adjacent rooms. The x rays must penetrate thick, dense materials with much higher energy than a medical x ray (9 MeV instead of less than 100 kiloelectronvolts). Also, the inspection must achieve a much higher resolution of 75 to 100 micrometers compared to the millimeter scale sufficient for medical applications.



Three collimators shape the x-ray beam into an inverted pyramid, which penetrates the test object and casts an x-ray shadow on the glass scintillator. The scintillator converts the x-radiation to green light, which is reflected by mirrors (not shown) onto four charge-coupled-device (CCD) cameras.

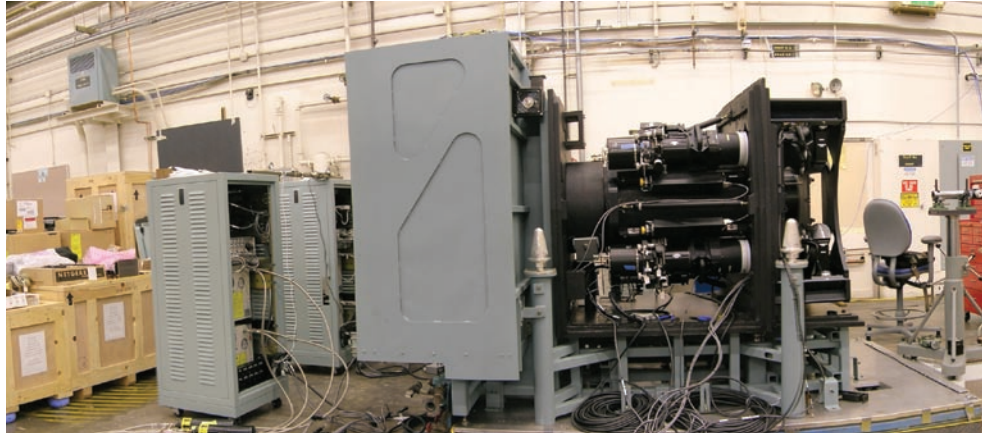
Prototype in 2000

Early work on a CT system for diagnosing weapon components began at Livermore in 2000. As proof of principle, physicist Gary Stone built a prototype system similar in overall design to CoLOSSIS, but it had just one camera instead of four and was capable of only 250-micrometer resolution. The prototype system's mechanical, electrical, and optical components worked well, and the feasibility of scanning was demonstrated using mock warhead components.

The initial results provided the impetus to build a more refined system with improved resolution. NNSA asked a team of Livermore scientists to work with Pantex managers in designing a CT system and to oversee its manufacture, assembly, and qualification. The resulting CoLOSSIS inspection system was built by OPTICS 1, Inc., with Livermore researchers and Pantex engineers providing technical assistance in specifying system requirements, design, setup, and operator training. Livermore computer scientist Dan Schneberk led the development of tomographic software.

In developing the optical and electronic requirements for CoLOSSIS, Livermore researchers originally specified one camera with an 8,000- by 8,000-pixel field of view. However, Trebes and Schneberk discovered that such a camera was not available commercially and would cost about \$25 million to design and build. As a result, OPTICS 1 designed an instrument using four 4,096- by 4,096-pixel digital cameras and a novel optical configuration for collecting and transferring images.

The movable CT system weighs almost 16 tons, excluding the x-ray source. Much of this weight comes from the lead shielding used to protect optical lenses, CCD camera chips, and sensitive electronics from the powerful x rays. The shielding includes a core of three lead "exhaust" tubes with 3.5- to 4.0-centimeter-thick walls and an outer array of large lead-lined removable shields supported by a steel exoskeleton. (See



CoLOSSIS was first assembled and tested at Livermore (shown here), then shipped to the National Nuclear Security Administration's Pantex Plant near Amarillo, Texas, where it was reassembled last year in a large x-ray inspection bay.

the figures on p. 17.) The removable shields permit personnel access to internal CoLOSSIS components.

CoLOSSIS at Work

A CoLOSSIS CT scan begins with the compact linear accelerator generating about 2,500 to 3,000 rads (unit of absorbed dose of ionizing radiation) per minute. Three sets of 2-inch-thick collimators shape the radiation source to precisely form an inverted pyramid of x rays optimized for the test object located about 6.5 meters away. The beam expands as it travels and is shaped by the collimators. Upon arrival at the test object, the beam delivers about 50 rads per minute.

The collimators are supported on a steel support frame attached to a linear rail transport system, allowing for easy movement forward and backward. Each collimator features four adjustable jaws made of tungsten alloy, an x-ray absorbing material. Once aligned, the collimators and jaws are locked into position because errors in alignment or the movement of collimator components could cause excessive x-ray scatter and possibly damage the CCD cameras.

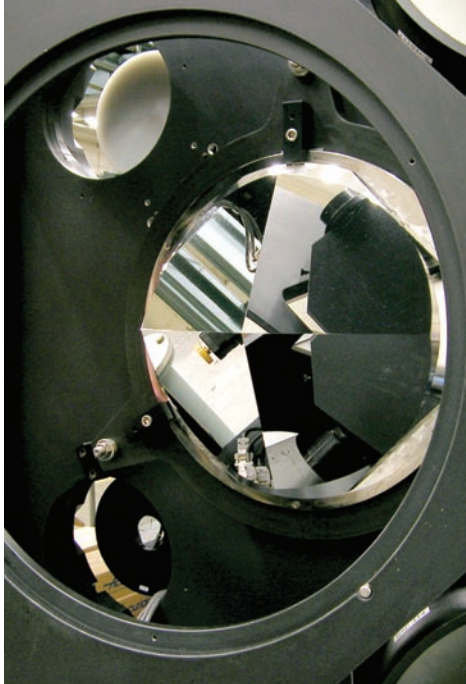
The shaped x-ray beam inscribes a cube measuring about 24 centimeters per side. A heavy, stable platform with a

precision-leveling system aligns the test object and holds it in position for CT data collection. The x rays penetrating the test object cast a shadow on a glass scintillator that converts the x radiation to green light (a wavelength of about 540 nanometers).

The light emitted from the scintillator is then bounced off a pyramid-shaped mirror. The light bounces in four different directions onto four identical 20-centimeter-diameter turning mirrors.

The turning mirrors then reflect the light onto four 16-megapixel CCD cameras. The cameras, similar in design to those used for terrestrial astronomy, are cooled to minus 100° C. OPTICS 1 designed the custom lenses, while the cameras were built by Spectral Instruments, Inc., with help from the University of Arizona. Each lens comprises eight elements arranged into six groups. The lenses image light onto each camera's 16-megapixel (4,096 by 4,096 pixels) CCD chip, equal to an active area of about 6 centimeters per side. The CCD chip converts light to voltage and provides 65,000 levels of gray.

The turning mirrors can be adjusted so that the light falls upon the four CCD cameras in perfect registration. By using two mirrors in each optical chain, the CCD cameras are shielded from the direct x-ray beam. "The CCDs have been pulled out



A pyramid-shaped mirror bounces green light from the scintillator in four different directions onto four identical turning mirrors. Fabricated by Corning, Inc., the pyramidal mirror was diamond-turned to an extremely smooth surface, plated with nickel, and then diamond-turned again to final optical specifications.

of the main beam path with a neat optical trick,” says Allen. Schneberk compares the mirror geometry to a periscope that permits observation without being in harm’s way.

Each digital image from the four CCD cameras is immediately downloaded to the adjoining control room, where four computer servers, one for each camera, are located. Control electronics for the cameras and cryogenic refrigeration systems are housed at the rear of the system, shielded from the direct x-ray beam. During operation, personnel remotely adjust the mirrors, lenses, and cameras from the control room.

The pyramid-beam-splitting architecture allows for the four images from the cameras to be seamlessly stitched together using Schneberk’s software. Each quadrant of the scintillator has a small overlap (20 to 50 pixels, about 1 percent) with the

adjacent quadrant to assist the stitching procedure. The software stitches the four separate images into one by eliminating the overlap and creating an 8,000- by 8,000-pixel radiograph.

Each of the four images contains 32 megabytes of information, for a total of 128 megabytes per stitched view. A typical scan comprises 1,500 digital radiographs, each requiring up to 90 seconds, and each separated from the next by a 0.24-degree rotational change. In all, the data set is about 192 gigabytes. Each image takes 30 to 90 seconds, with 1,500 views requiring about 72 hours, spread over several days.

The complete data set is transferred to Lawrence Livermore or Los Alamos, where the individual images are reconstructed into an approximately 1-terabyte 3D file using

Seeing the Invisible with X Rays

X rays, a form of electromagnetic radiation, have a wavelength ranging from 10 to 0.01 nanometers (billionths of a meter), which corresponds to frequencies ranging from 30 petahertz to 30 exahertz (30×10^{15} to 30×10^{18} hertz) and energies ranging from 120 electronvolts to 120 kiloelectronvolts. Their discoverer, Wilhelm Conrad Röntgen, called them x rays, meaning an unknown type of radiation.

X-ray radiography is a nondestructive testing technology used to examine the interior of objects. It operates on the principle of dissimilar transmission of x rays through different materials. The ability of a material to block x rays increases with its density. Therefore, images of different materials will have varying contrasts.

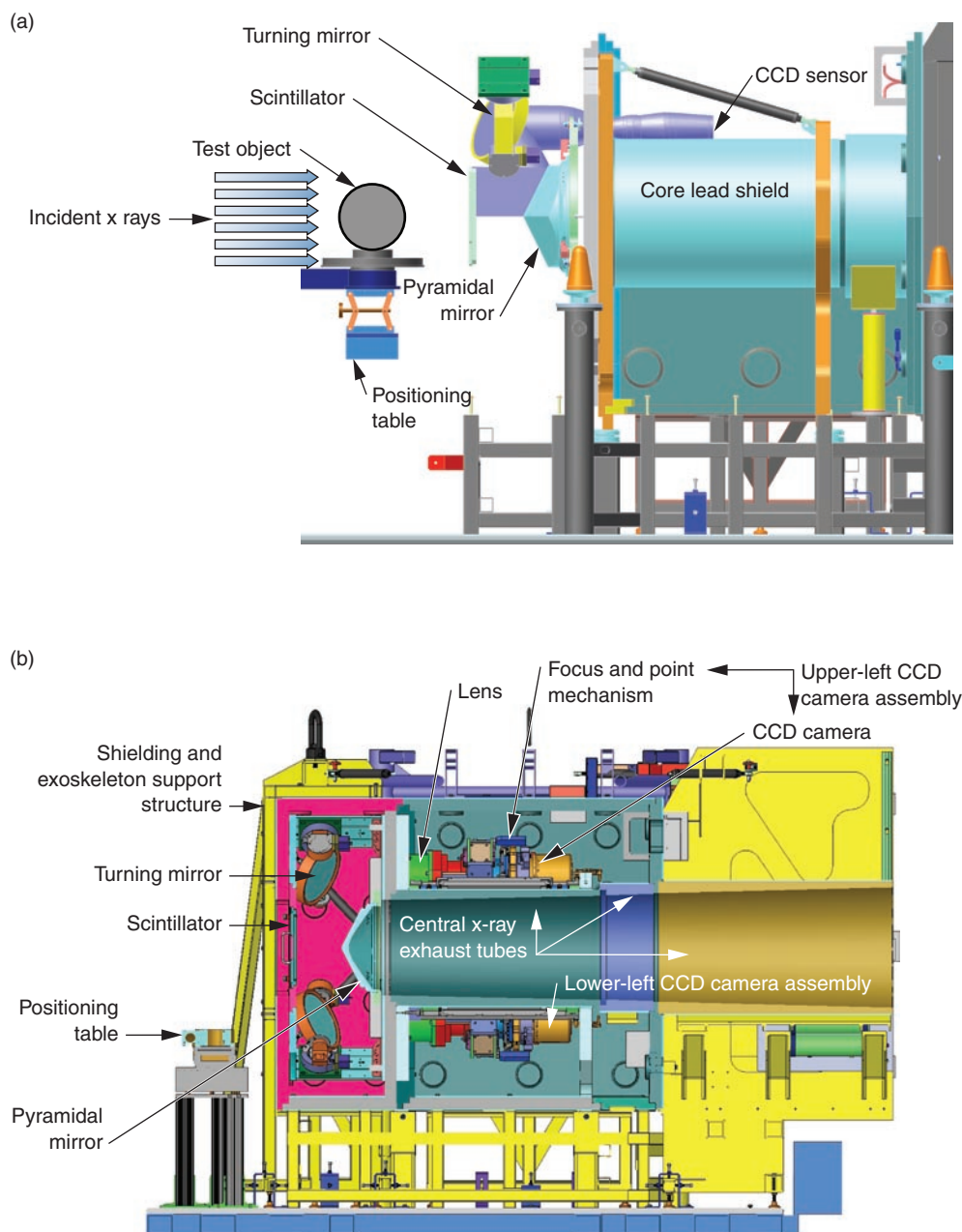
Using x rays is a long-established method to see inside objects, from human limbs to airplane parts. Because x rays are highly penetrating, they are useful in medical diagnostics, where x rays pass through organs onto a photographic cassette. Areas where radiation is absorbed appear as lighter shades of gray.

A typical modern x-ray machine has a filament that produces an electron beam used to excite a target into producing x rays. The transmitted x rays pass through an object, are collected by a detector, and then translated into amplified electric signals. These signals are then transformed into an x-ray image. The densities of the various materials comprising a specimen allow different amounts of x rays to pass through, resulting in varying grayscale levels on the x-ray image.

Livermore scientists use x rays to understand the properties of matter, from nuclear weapons to viruses to black holes. On a large scale, scientists are developing high-energy tomographic systems with spatial resolutions significantly better than anything currently available, requiring specialized computers and advance

image-analysis methods. For example, they are developing systems for nuclear weapons stockpile surveillance, cargo container inspection for the Department of Homeland Security, spacecraft component certification for the National Aeronautics and Space Administration, and a wide range of industrial applications. On a much smaller scale, researchers are developing x-ray optics for cameras with a resolution as small as 10 microns to image mice used in research. On the very smallest scale, they are collaborating with others on developing x-ray free-electron lasers with atomic resolution to image single molecules, protein complexes, and viruses.

Livermore researchers require powerful x rays for such applications as backlighting inertial confinement fusion experiments for the National Ignition Facility and for imaging still or exploding materials for the National Nuclear Security Administration’s (NNSA’s) Stockpile Stewardship Program. Unlike x-ray radiography used to image stationary objects at NNSA’s Pantex Plant, the flash x-ray facility at Livermore’s remote Site 300 produces powerful x rays to freeze the motion of materials moving at ultrahigh speeds. These nonnuclear “hydrodynamic” experiments study the behavior of a nuclear weapon from high-explosive ignition to the beginning of the nuclear chain reaction. These experiments consist of imploding inert (nonfissile) material with a high explosive. The explosive compression replicates the effects in the core of a nuclear device. (See *S&TR*, September 2007, pp. 4–11.) Flash x-ray tests combined with x-ray radiography of nuclear components at Pantex are two critical procedures aimed at ensuring the reliability and safety of the U.S. nuclear deterrent.



(a) A side view diagram of CoLOSSIS without its outer lead shielding shows the location of major components. A beam of x rays penetrates the test object positioned in front of the detector's scintillator. The scintillator converts the x radiation to green light, which is then reflected by a pyramidal mirror to four turning mirrors that bounce the light onto four identical charge-coupled-device (CCD) cameras. The positioning table rotates the object 360 degrees in increments. About 1,500 radiographic images are then assembled using Livermore-developed software into one large three-dimensional image for viewing. (b) A cutaway view shows the central x-ray exhaust tubes. This view includes just two of the four cameras and two of the four turning mirrors.

Livermore-developed software. "Joining all 1,500 2D images into an incredibly detailed 3D image takes several days of computer time," says Stone.

To view the 3D image, computer scientists combine four 3,200- by 2,300-pixel monitors to form essentially one large monitor. A weapons scientist can "walk through" the test object for an overall look in any direction or zoom in on a tiny subsection and proceed micrometer by micrometer deep into a part.

15-MeV System on the Horizon

CoLOSSIS is currently undergoing final shakedown prior to beginning scheduled inspections. "The goal is to make sure the system is usable by Pantex technicians," says Stone. In the meantime, discussions have begun on designing one or more 15-MeV CT scanners for Pantex. Much of the motivation for higher-energy systems is the possibility that scan times could be reduced, perhaps dramatically. Stone notes that higher energy will require more space in a larger bay and thicker shielding.

For the next several years, however, the 9-MeV CoLOSSIS system will provide a vital opportunity for NNSA to inspect stockpiled weapons more efficiently and thoroughly than current technology permits as well as provide scientists with a technical basis for future CT designs. Says Allen, "We're seeing more than ever before." For weapons scientists, seeing more means greater confidence in aging nuclear weapons—and in America's national security.

—Arnie Heller

Key Words: Combined Large Optical Scintillator Screen and Imaging System (CoLOSSIS), computed tomography (CT), nondestructive evaluation, Pantex Plant, radiography, stockpile stewardship, x ray.

For further information contact Pat Allen (925) 423-8955 (allen42@llnl.gov).

Mass-Producing Positrons

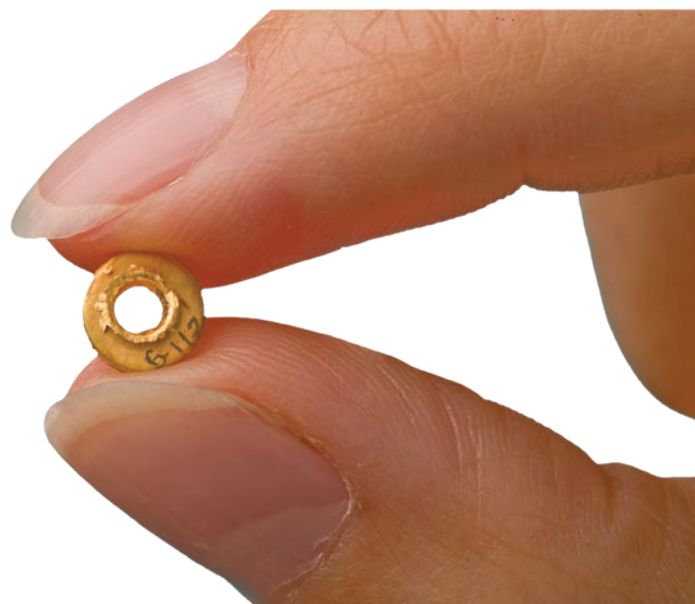
HOW do black holes form? Where do gamma-ray bursts originate in space? Why does matter dominate over antimatter in the universe? No one really knows. However, through the study of positrons, the antiparticles of electrons, scientists believe they may gain insight into these complex astrophysical questions.

Positrons are elementary particles whose physical properties, such as spin and mass, are the same as electrons, except that positrons have a positive charge. For years, scientists have theorized that lasers could be used to generate positrons in a laboratory by “zapping” an ultrathin micrometer-size foil target made of a high-atomic-number (high-Z) material, such as gold or tantalum. Researchers at Livermore recently showed that targets thicker than a few micrometers are a more efficient mechanism for positron generation. Using an ultraintense, short-pulse laser and millimeter-thick targets, physicists Hui Chen and Scott Wilks have produced more than 100 billion positrons—an unprecedented number of laser-generated positrons.

Particle accelerators are typically used to generate positrons for antimatter research. Livermore’s new laser-based method can generate similar numbers of positrons but in a fraction of the time—all positrons are generated in less than 100 picoseconds. With the capability of generating billions of positrons inside a small laboratory, scientists have a way of making antimatter more accessible, opening the door to new avenues of research. As a result, they may be able to uncover answers to some of the most perplexing questions about our universe. This new capability may also provide scientists with a better way to produce positronium—the short-lived bound state of an electron and a positron—which could enable the development of advanced, extremely high-powered gamma-ray lasers.

Larger Target, Greater Yield

Chen and Wilks began their research in 2003 as part of a project funded by Livermore’s Laboratory Directed Research and Development (LDRD) Program. “At the time,” says Chen, “researchers thought that only ultrathin foil targets could be used to create the hot electrons needed to generate positrons.” For this earlier study, Chen and Wilks created an experimental method using ultrathin targets and developed instrumentation for detecting the positrons. The method required an intense laser to accelerate



Livermore’s new laser-based method to produce positrons uses targets made from a variety of high-atomic-number (high-Z) materials ranging in thickness from 250 micrometers to 3 millimeters. The 1-millimeter-thick gold target shown here was shot by the Laboratory’s Titan laser. The best experimental results were achieved using the thickest targets.

electrons to energies just over 1 megaelectronvolt. In what is known as the trident process, hot electrons interact with the nuclei of atoms within the target, producing a virtual photon that quickly converts to an additional electron and a positron.

Wilks, who designed the experiment for the LDRD project, used computer models to predict the number of positrons that would be generated as a function of the thickness of the target and the intensity of the laser. Chen, who performed and led the experiment, devised a detection scheme for positrons based on an existing electron spectrometer. They conducted their test on a laser at the Rutherford Appleton Laboratory in England. “We were allowed just one shot on the laser,” says Chen. “Unfortunately, it yielded only a hint of a positron signal.”

For their current LDRD study, Chen and Wilks improved their experimental design and detection methods. These experiments were performed in Livermore’s Jupiter Laser Facility on the Titan laser, which was completed in 2006, one year after the team’s initial experiments in England. Titan has a unique long- and short-pulse capability: A high-energy, petawatt short-pulse (subpicosecond) beam is coupled with a kilojoule long-pulse (nanosecond) beam. (See *S&TR*, January/February 2007, pp. 4–11.) With Titan, the team had a local, more accessible tool for proving their experimental design.

Initial experiments on Titan revealed new data on the distribution and energy of hot electrons interacting with

materials. Wilks took these hot electron measurements and put them into a computational model. “The model calculated the electron distribution in the target, and how many positrons were produced in the process,” says Wilks. “After reviewing the simulation results, I realized that irradiating thicker targets would result in orders of magnitude more positrons than seen in previous experiments.”

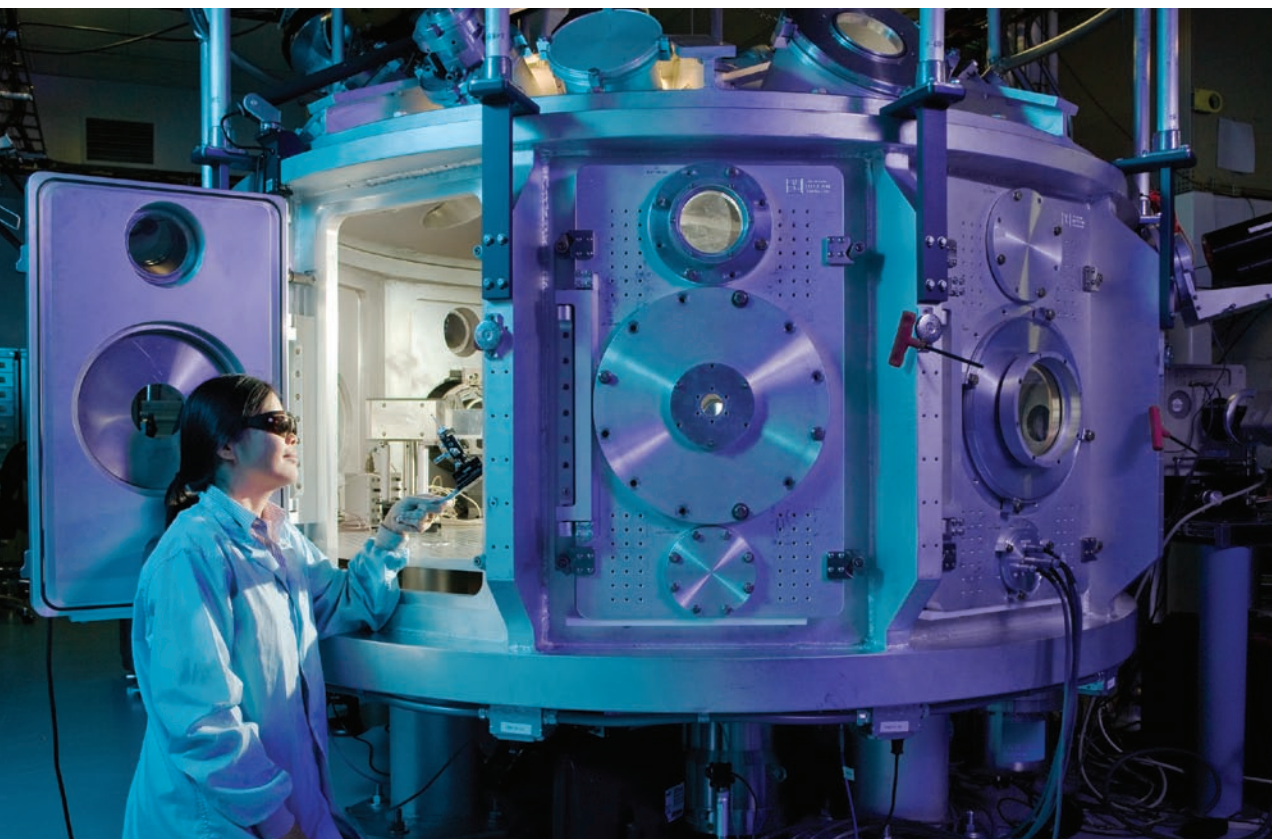
The thicker targets increase the number of interactions that can occur inside the target. In addition, a different physical process—the Bethe–Heitler process—dominates in larger targets and promotes positron generation on a greater scale. To more accurately detect this abundance of antimatter, Chen redesigned the electron–positron spectrometers using more elaborate components to make them more sensitive to the positron signals.

Producing Particle Pairs

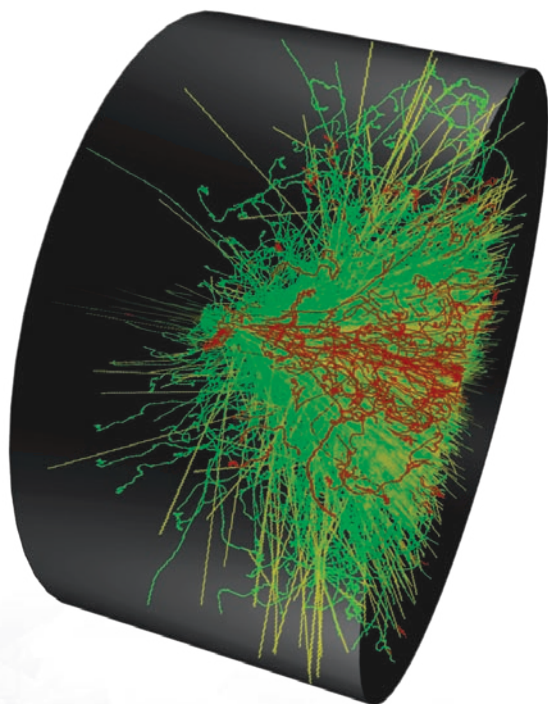
Chen developed new, larger targets using a variety of materials, from aluminum to gold. The targets ranged in thickness from 100 micrometers to 3 millimeters. Each target was shot with two laser pulses in close succession. The first pulse lasted a nanosecond

and delivered 100 joules of energy to the target. This initial blast created a plasma on the surface of the material that contained electrons and ions. The second laser shot was an ultraintense pulse— 10^{19} watts of energy per square centimeter—that lasted only picoseconds but was powerful enough to accelerate electrons within the plasma. “For other studies, this plasma is not always ideal because researchers want to accelerate the electrons to lower energies,” says Chen. “We can get three or four times more positrons by using the plasma to generate 10- to 100-megaelectronvolt higher-energy electrons.” These electrons are blasted into the target, which acts as a catalyst to induce particle interactions.

Within the target material, the electrons move at relativistic speeds with kinetic energies ranging from 6 to 100 megaelectronvolts. Through the Bethe–Heitler process, these high-energy electrons lose energy as they interact with the material’s nuclei, resulting in the emission of high-energy bremsstrahlung photons. These photons in turn interact with the high-Z nuclei, which enables some of the high-energy photons to split into electron–positron pairs (matter and



Inside Livermore’s Jupiter Laser Facility, physicist Hui Chen conducts positron experiments on Titan, a laser that couples a high-energy, petawatt short-pulse (subpicosecond) beam with a kilojoule long-pulse (nanosecond) beam.



Simulations show the electron-positron-photon shower from a positron experiment. When the laser strikes the target (from the left), high-energy electrons (green) are generated that then lose energy as they interact with the target material's nuclei, emitting high-energy bremsstrahlung photons (yellow). Some of the high-energy photons then interact with the nuclei, creating pairs of electrons and positrons (red). A number of positrons then leave the target (out the right) and are detected by positron spectrometers. (Rendering by Kwei-Yu Chu.)

antimatter) based on Einstein's $E = mc^2$ formula that relates energy and matter. The energies of the photons are proportional to the energies of the decelerating electrons as they interact with the material. The higher the energy, the more likely the bremsstrahlung photons will produce electron-positron pairs, a large fraction of which are inevitably blasted out the back of the target in a plasma jet.

The positron energy in the plasma jet was measured by two of the redesigned spectrometers positioned at various angles around the back of the target. However, the plasma jet does not contain the total amount of positrons generated, such as those still in the target. The data recorded from the spectrometers is compared with computer simulations to infer how many pairs were created overall. Chen and Wilks directly detected more than 1 million particles per laser shot. They infer that a total of about 100 billion positron particles were produced. Using targets less than 200 micrometers thick, the research team found that the positron signal fell below the detection limit of the spectrometers. The most successful results were produced using 1- to 3-millimeter-thick gold targets.

A Wealth of Possibilities

The new method for positron generation designed by Chen and Wilks has the potential to advance antimatter research. Studying the gamma rays produced when positrons and electrons annihilate each other may help researchers better understand gamma-ray bursts that occur in space. In addition, the method could be used to generate a high-yielding positron source for particle accelerators. The method could also provide a more efficient way to generate positronium gas. Current production methods require positronium gas to be contained in magnetic traps that must be filled repeatedly to obtain the amount needed for research purposes. "Instead of producing positronium gas in small increments over time, we can in principle produce the amount needed for research in a few picoseconds," says Chen.

"The results of this experiment are so new, we have not even begun to investigate all the potential applications," says Wilks. In the meantime, scientists have a new mechanism by which they may be able to unravel antimatter's secrets. While it may be decades or longer before scientists know enough about antimatter to significantly increase their understanding of the origins of our universe, the research done by Wilks and Chen could move them one step closer to the answers.

—Caryn Meissner

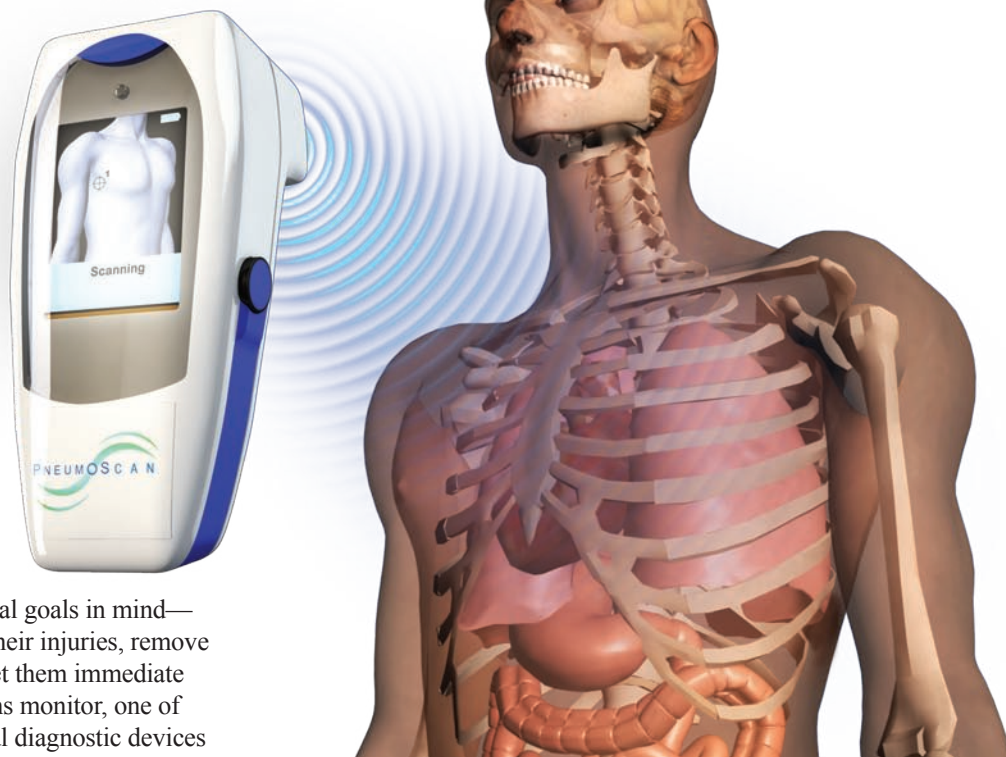
Key Words: antimatter, astrophysics, gamma ray, high-Z material, hot electron, plasma, positron, positronium, Titan, ultraintense laser.

For further information contact Hui Chen (925) 423-5974 (chen33@llnl.gov) or Scott Wilks (925) 422-2974 (wilks1@llnl.gov).

The Next Generation of Medical Diagnostic Devices

AS search and rescue teams scour the rubble of fallen buildings, they have several goals in mind—locate the survivors, determine and stabilize their injuries, remove them from the hazardous environment, and get them immediate medical care. A Livermore-designed vital signs monitor, one of several ultrawideband- (UWB-) based medical diagnostic devices being developed at the Laboratory, can detect the respiratory rhythms of living individuals among the debris, expediting help from search and rescue personnel. Livermore's noninvasive pneumothorax (air trapped in the chest cavity) detector and intracranial hematoma (blood in the brain) detector could also offer first responders a quicker method for identifying life-threatening health conditions in emergency situations, thus improving a victim's chance of survival. Additionally, all three of these diagnostic tools could be tremendously beneficial to the future of patient care by providing an inexpensive means for continuous health monitoring. UWB technology makes them possible.

UWB signals are extremely short electromagnetic pulses (50 to 1,000 picoseconds) that are transmitted across a broad range of radio frequencies over several gigahertz. During the mid-1990s, Livermore scientists and engineers coupled a UWB antenna with an ultrafast digitizing laser diagnostic system to create an extremely low-power, high-fidelity system known as micropower impulse radar. (See *S&TR*, September 2004, pp. 12–19.) These systems transmit millions of UWB pulses in less than a second and then receive the signals when they are reflected off nearby objects. Funded in part by the Laboratory Directed Research and Development Program, engineer John Chang is working with scientists and engineers from Livermore and other research institutions to leverage this UWB technology for creating portable, noninvasive, nonhazardous medical diagnostic devices that can detect cardiac and respiratory conditions and thoracic and brain trauma.



Livermore-developed handheld ultrawideband devices, such as the pneumothorax detector shown here, transmit and receive nonhazardous electromagnetic pulses that propagate through specific areas of the human body and are reflected by tissue, fluid, and air. (Rendering by Kwei-Yu Chu.)

The vital signs monitor, pneumothorax detector, and intracranial hematoma detector are being developed as handheld devices that can be used outside of hospitals. They will complement existing medical diagnostic tools currently available only inside a hospital environment, such as computed tomography (CT), magnetic resonance imaging, and x-ray machines. UWB devices are also relatively more affordable and nonhazardous to human health. “Our noninvasive devices require no direct contact with the patient and emit only nonionizing radiation,” says Chang, who leads the development effort. Livermore’s medical diagnostic devices may become invaluable tools for first responders and could be further adapted for patients’ in-home use.

Pulses in Time

Although the three devices have different designs and applications, the fundamental operation of each relies on effectively processing micropower UWB signals. A transmitter, or array of transmitters, inside the devices sends out directed UWB pulses. These extremely low-power electromagnetic signals can penetrate a variety of materials, such as human body tissue

and fluids. Using various range-finding techniques, a receiver in the device captures these signals when they are reflected off an object within a preset distance over time. The received signals are digitized, processed, and stored in a computer. Reconstructive mathematical algorithms are used to analyze and interpret the data and can provide results in real-time.

The signals reflected back to the device vary from their original transmitted form. Their characteristics, such as frequency and resonance, are changed depending on the properties of the material with which they interact. Through extensive research and clinical trials on human subjects, the Livermore team has developed baseline data for each of the devices that indicate the differences between reflected signals from healthy patients and those suffering from specific health conditions, such as an intracranial hematoma. Each device correlates patient-specific data with these baselines, thus enabling users to detect abnormalities. "Through this research, we have a better understanding of how signals are characterized based on the physiological properties of materials," says Chang.

Despite their intricate operation, Livermore's medical diagnostic devices use very little power, operating on standard consumer batteries. Their low-power requirements and ability to transmit pulses in UWB make them resistant to background noise and unlikely to interfere with other electromagnetic equipment operating within the same time, frequency, and space. "Our devices

are quite sensitive and can detect extremely subtle signatures in complex environments," says Chang.

A Two-Fold Purpose

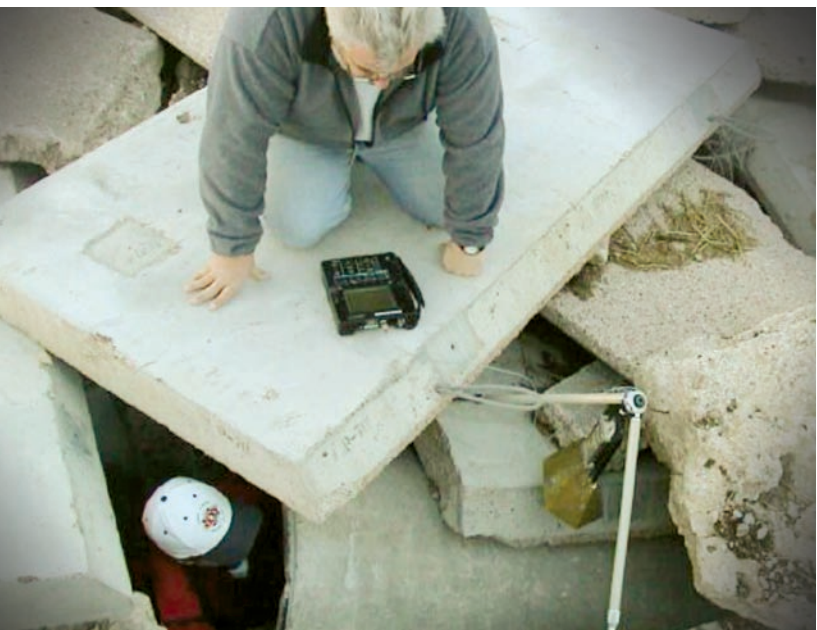
As a result of Livermore's efforts, the vital signs monitor can be modified in form and function. It can be used as an electronic stethoscope that provides two key signatures corresponding to cardiac and respiratory vital signs. In another form, the device can detect the respiration of a victim trapped beneath collapsed structural debris. According to Chang, "The electromagnetic signals generated by this technology can penetrate through a broad range of materials, allowing us to determine not only the absence or presence of live humans underneath structural debris but also the state of health of any survivors." A prototype device that incorporated hardware and signal processing capabilities was used as part of the concerted search and rescue efforts to look for survivors at ground zero of the World Trade Center following the September 11, 2001, attacks and in New Orleans after Hurricane Katrina in 2005.

How the device is operated in a given situation depends on the user's needs. Whereas search and rescue teams would tap the device's motion-sensing capabilities to locate survivors, emergency medical response personnel might use the device to determine whether a person is going into cardiac or respiratory failure. Under the oversight of Livermore's Institutional Review Board, which ensures that all work by Laboratory staff involving human subjects meets appropriate regulations regarding subjects protection, studies revealed that rhythms obtained on the vital signs monitor directly correlated to data recorded from echocardiograms and pulse oximeters. "These studies have shown strong indications that this type of technology could be sensitive enough to eventually track cardiac arrhythmias," says Chang. The Livermore team is currently evaluating how the technology could be used in long-term care environments such as dialysis centers and for telemedicine.

Dangerous Blood and Air

The intracranial hematoma and pneumothorax detectors are designed for diagnosing traumatic injuries to the head and chest. These types of injuries occur in combat and traumatic accidents. The intracranial hematoma detector identifies localized pools of blood underneath the skull that result from ruptured blood vessels. The pneumothorax device detects air trapped in the pleural area between the wall of the chest cavity and the lung. In both cases, immediate diagnosis is essential to prevent further complications and potentially even death, which can occur within minutes to hours under certain conditions. These devices could enable the fast triage and treatment decisions needed to save lives.

The intracranial hematoma detector has undergone its initial testing and has the potential to help a large number of people.



In prototype tests of the Livermore-developed vital signs monitor, engineer Patrick Welsh uses the device to successfully detect the respiratory rhythm of a person hidden underneath concrete debris.



The intracranial hematoma detector can detect localized pools of blood located between the skull and the upper portion of the brain—an injury typically resulting from trauma to the head. (Rendering by Kwei-Yu Chu.)

“According to the Centers for Disease Control and Prevention, 1.4 million people per year in the U.S. sustain traumatic brain injuries,” says Chang. This device could help medics in the field determine the size and location of a hematoma and if the condition is life-threatening. In addition, hospitals could use the device to monitor trauma patients in critical condition from their bedside rather than moving them every few hours for a CT scan. It also reduces patient exposure to the harmful ionizing radiation emitted by those scans.

The intracranial hematoma detector operates much like the vital sign monitor except that it receives UWB signals reflected off blood masses rather than off heart and lung tissues. Pooled blood is anomalous within the skull and has different dielectric properties than the surrounding healthy tissue or normal perfusing blood, so the characteristics of signals reflected off blood masses are notably different. The same is true for pneumothorax because air trapped in the chest cavity has different properties than the air processed normally through lung tissues.

The idea for the pneumothorax device came from Chang’s 15 years of experience serving in the search and rescue community. Prior to the development of this device, medical responders would have to physically examine the patient for signs of respiratory

distress, listen to their breathing with a stethoscope—a challenge in noisy environments—and then transport the patient to a hospital for a CT scan or chest x ray before positively identifying pneumothorax. With this new detector, medics on the scene can determine whether the patient has the condition and how much air is trapped, reducing the chance of exacerbating the already life-threatening condition. Patients can also use the device to monitor themselves from home if their condition is sufficiently mild and does not require hospital care.

The Laboratory received an R&D 100 Award for the technology in 2007 (see *S&TR*, October 2007, pp. 4–5), and the pneumothorax detector has completed initial clinical studies. Livermore has two Cooperative Research and Development Agreements and two commercial licenses with ElectroSonics Medical, Inc., formerly known as BIOMECH, Inc., for commercializing the technology. The company continues to work with the Laboratory to enhance the device and perform additional clinical studies. Livermore and ElectroSonics Medical were also selected for the 2009 Excellence in Technology Transfer Award, which is sponsored by the Federal Laboratory Consortium for Technology Transfer.

Remote Sensing

Future modifications to these devices will extend their capabilities for imaging purposes and further improve care in environments where medical resources are limited, such as in rural and combat areas. “The vital signs monitor is being modified so that it can be integrated into soldiers’ protective gear for continuous monitoring,” says Chang. This adaptation would allow commanders and medics to have a tool for monitoring a soldier’s health remotely. “One advantage of all our devices is that direct skin contact is not required for an accurate reading.” In addition, the Livermore team is working to modify the intracranial hematoma detector for detection and characterization of brain injuries unrelated to trauma, such as stroke.

Livermore’s UWB technology has enabled the development of advanced medical technologies and provided mechanisms for improving patient care in almost every possible setting. “These devices could have a broad impact in environments where medical resources are limited or even nonexistent, whether it’s on the Moon or next door,” says Chang. UWB makes the devices possible; the Livermore team makes them a reality.

—Caryn Meissner

Key Words: intracranial hematoma detector, medical diagnostic device, micropower impulse radar, noninvasive pneumothorax detector, R&D 100, ultrawideband (UWB), vital signs monitor.

For further information contact John Chang (925) 424-4624 (chang16@llnl.gov).

In this section, we list recent patents issued to and awards received by Laboratory employees. Our goal is to showcase the distinguished scientific and technical achievements of our employees as well as to indicate the scale and scope of the work done at the Laboratory.

Patents

Biobriefcase Electrostatic Aerosol Collector

Perry M. Bell, Allen T. Christian, Christopher G. Bailey, Ladona Willis, Donald A. Masquelier, Shanavaz L. Nasarabadi

U.S. Patent 7,503,229 B2

March 17, 2009

This system for sampling air and collecting particles entrained in the air includes a receiving surface, a liquid input that directs liquid to the receiving surface, an air input that directs air with entrained particles to the liquid surface, and an electrostatic contact connected to the liquid that imparts an electric charge to the liquid. The particles that may potentially include bioagents become captured in the liquid. Collection efficiency is improved by the electrostatic contact electrically charging the liquid. The effects of impaction and adhesion from electrically charging the liquid result in a highly efficient particle capture medium with a low fluid-consumption rate.

Biobriefcase Aerosol Collector Heater

Perry M. Bell, Allen T. Christian, Christopher G. Bailey, Ladona Willis, Donald A. Masquelier, Shanavaz L. Nasarabadi

U.S. Patent 7,503,230 B2

March 17, 2009

This detection system is used to sample air and collect particles entrained in the air. These particles may potentially include bioagents. A sample of air entrained with particles is directed to a receiving surface. A liquid is also directed to the receiving surface thereby producing a liquid surface, wherein the particles become captured in the liquid. The liquid and particles are heated to lysis any potential bioagents.

Amphiphilic Mediated Sample Preparation for Micro-Flow Cytometry

David S. Clague, Elizabeth K. Wheeler, Abraham P. Lee

U.S. Patent 7,504,265 B2

March 17, 2009

This flow cytometer includes a flow cell with oil and water phases, an oil–water interface between the two phases, and a device for detecting the sample at the oil–water interface. A hydrophobic unit is connected to a sample and placed in the flow cell. The sample is detected at the oil–water interface.

Awards

Laboratory scientists and engineers received three awards for **Excellence in Technology Transfer** from the **Federal Laboratory Consortium (FLC) for Technology Transfer**. Livermore won its awards for a process that removes silica from geothermal waters, a pneumothorax detector, and a unique technology transfer effort that could strengthen U.S. maritime security. “On behalf of the Industrial Partnerships Office [IPO], it is my pleasure to offer congratulations to the Lab employees who have been honored,” said Erik Stenehjelm, director of Livermore’s IPO.

Those receiving awards for the silica mining effort include former Livermore researchers **Bill Bourcier** and **Carol Bruton** (now at Simbol Mining); IPO business development executive **Leah Rogers**; Livermore patent attorney **Eddie Scott**; **Cindy Atkins-Duffin** of the Laboratory’s Global Security Principal Directorate; and **Luka Erceg**, president of Simbol. Recipients of the FLC award for the pneumothorax detector include Livermore researcher **John Chang**; IPO business development executive **Genaro Mempin**; and Enviromaster International, LLC, president and chief operating officer **Robert Purcell**. Team members also recognized the contributions of IPO’s **Alicera Aubel**, who worked on the project’s two Cooperative Research and Development Agreements, and resource analyst **Maria Strain**. Among those receiving the award for technology to strengthen U.S. maritime security are Livermore researchers **Bill Dunlop**, **Arden Dougan**, **Norm Madden** (retired), **Dave Trombino**, **Kique Romero**, and **Peter Haugen**; IPO business

development executive **Annemarie Meike**; **Frank Swanson** and **Brian Adlawan** of Textron Systems; former Livermore employee **Dan Archer** of Oak Ridge National Laboratory; **Douglas Franco** and **Dirk Langeveld** of Secure Box Corporation; and **Alex Bordetsky** of the Naval Postgraduate School.

FLC is a nationwide program that helps link federal laboratory mission technologies and expertise with the marketplace. The awards were presented May 7, 2009, during the FLC’s four-day national technology transfer meeting in Charlotte, North Carolina.

Dylan Rood, a Lawrence Scholar working in the Laboratory’s Center for Accelerator Mass Spectrometry (CAMS), was selected as a **top student presenter** at the **Seismological Society of America** annual meeting in Monterey, California—an honor that goes to just 10 to 15 percent of all student presenters each year. The award-winning presentation, “Dating Offset Alluvial Fans along the San Andreas Fault in the Santa Cruz Mountains Using LiDAR and Beryllium-10 Geochronology,” highlights the research conducted with a team from CAMS using light detection and ranging–(LiDAR-) based geomorphic mapping and cosmogenic beryllium-10 surface-exposure dating. Rood is completing his Ph.D. at the University of California at Santa Barbara, where he is studying tectonic geomorphology and Earth surface processes related to earthquakes.

Preventing Close Encounters of the Orbiting Kind

Lawrence Livermore, in collaboration with Los Alamos and Sandia national laboratories and the Air Force Research Laboratory, is working to improve the nation's capabilities for detecting and monitoring threats to U.S. space operations. Since early 2008, a team of computational physics and engineering experts at Livermore has been designing a comprehensive set of analysis, modeling, simulation, and visualization tools that together are called the Testbed Environment for Space Situational Awareness (TESSA). An initial goal of the project is to provide a high-fidelity model of the U.S. Air Force's Space Surveillance Network, whose task is to know the location of objects orbiting Earth and enable a more accurate assessment of whether or not any of these objects poses a threat to any active satellites. Even a tiny object the size of one's thumb would inflict massive damage when moving at several kilometers per second. The U.S. Air Force Space Command and the National Reconnaissance Office have joined together to create a new national program to coordinate space-protection activities across the military and intelligence communities. TESSA is now being used to support these space-protection activities and could eventually be fully integrated into the Air Force's Joint Space Operations Center.

Contact: Scot Olivier (925) 423-6483 (olivier1@llnl.gov).

A CAT Scanner for Nuclear Weapon Components

Lawrence Livermore researchers have developed a computed tomography x-ray system to image nuclear weapon components at the National Nuclear Security Administration's Pantex Plant in Texas. The Confined Large Optical Scintillator Screen and Imaging System (CoLOSSIS) consists of a scintillator; a pyramid-shaped central mirror; four turning mirrors; and four high-resolution, low-intensity visible-light charge-coupled-device cameras. CoLOSSIS uses a 9-megaelectronvolt x-ray beam to take 1,500 separate radiographic images of a test object rotated in increments over 360 degrees. The radiographs are then assembled, using Livermore-developed algorithms, to provide a three-dimensional image with greater resolution than previously achieved using a 9-megaelectronvolt x-ray system. Scientists can "walk through" the image to discover any problems or anomalies. CoLOSSIS is now undergoing final qualification at Pantex before beginning scheduled weapon inspections. Data gathered at Pantex will be reported to scientists and engineers at Lawrence Livermore and Los Alamos national laboratories, the two centers of nuclear weapon design and engineering.

Contact: Pat Allen (925) 423-8955 (allen42@llnl.gov).

Remembering Herb York (1921–2009)



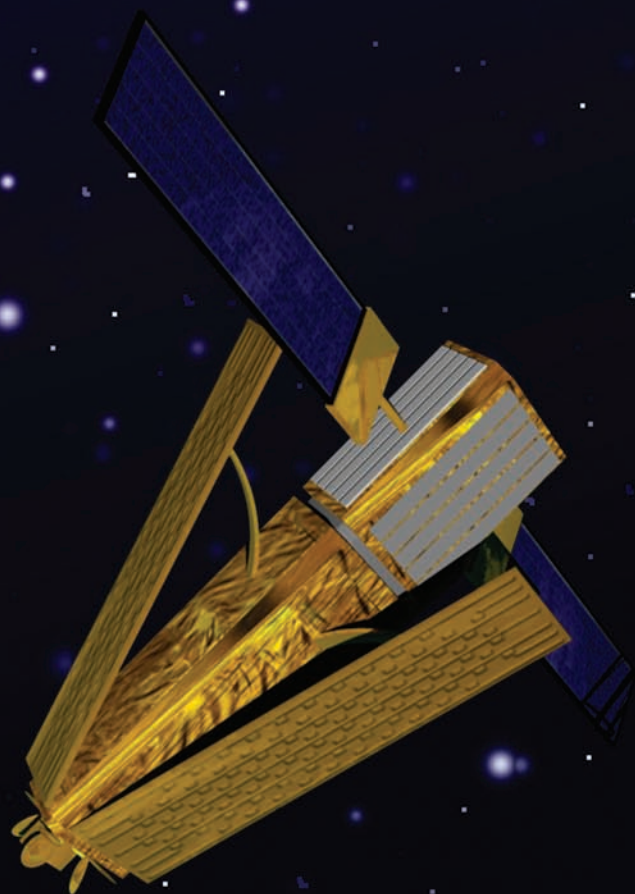
The Laboratory's first director had a leading role in creating a series of innovative institutions, including Lawrence Livermore and the University of California campus at San Diego.

Also in September

- *A compact instrument that identifies DNA will help researchers discover new marine species and search for extraterrestrial life.*
- *An experimental method that converts sound waves into light may lead to improved scientific and industrial applications.*
- *Lawrence Livermore is one of few organizations that distills data on U.S. energy resources into easy-to-read flow diagrams.*

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